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Microgravity Fluid Management Symposium

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Proceedings of a symposium held at
NASA Lewis Research Center
Cleveland, Ohio
September 9-10, 1986

NASA

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NASA
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and Space Administration

Scientific and Technical
Information Branch

1987

FOREWORD

Within NASA, the Office of Aeronautics and Space Technology (OAST) has the responsibility for timely development of needed new technologies. In October 1985, OAST sponsored an In-Space Research, Technology, and Engineering (RT&E) Workshop that marked NASA's initiation of a long-term outreach program to focus the needs of universities, industry, and government for in-space experiments and to begin building a strong user constituency for space research and engineering. That workshop provided a forum for developing an initial plan to involve universities, industry, and other government agencies with NASA in establishing structure and content for a national In-Space RT&E program.

At the workshop in Williamsburg, seven theme areas were identified for the RT&E program, including one titled "Fluid Management." That workshop also formed the basis for establishing ongoing working groups that will continue to develop and coordinate the requirements for in-space RT&E activities.

The Microgravity Fluid Management Symposium was held at Lewis Research Center on September 9 - 10, 1986, as an element of the ongoing In-Space RT&E activity. The objectives of the symposium were to (1) review space applications that require fluid management, (2) determine the current status of technology development, and (3) identify future research and technology development requirements.

This publication is a compendium of the information presented at the symposium. The preface briefly summarizes the conclusions of the symposium.

Sverdrup Technology, Inc. assisted with conference preparations and edited the conference publication.

Richard W. Vernon
Symposium Chairman

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PREFACE

The Microgravity Fluid Management Symposium, sponsored by NASA's Office of Aeronautics and Space Technology (OAST), was attended by 117 persons representing industry, universities, and several government agencies, including NASA, DOE, and DOD. The purpose of the symposium was to continue the development of a fluid management program element, within OAST's In-Space Research, Technology, and Engineering (RT&E) program, that was initiated at a workshop in Williamsburg, Virginia, in October 1985. The symposium provided a forum to review space applications that require fluid management technology, to present the current status of technology development, and to identify the technology developments required for future missions. The symposium consisted of 19 technical presentations with discussion at the completion of each presentation; it also included a general discussion at the conclusion of the symposium.

Several general recommendations emerged from the symposium in addition to the specific recommendations made during the technical presentations. The general recommendations follow:

1. A committee should be established to develop and coordinate a comprehensive fluid management program within NASA and also to provide a central contract for facilitating the exchange of information with other agencies.

2. There is an acute need to study the fundamentals of fluid behavior in reduced gravity to provide a data base that can be used in developing the required technologies.

3. In the near term, researchers should emphasize ground-based experimental facilities such as drop towers and aircraft to obtain appropriate experimental data.

4. Researchers should also clearly define the requirements for facilities that will provide the capability for future in-space experimentation related to fluid behavior.

The following is a summary of the topics that were discussed during the technical presentations:

- Session 1 - Fluid Storage

  Multilayer insulation
  Low thermal conductance supports
  Fluid sloshing
  Para to ortho conversion of hydrogen
  In-space refrigeration
  Fill techniques and procedures
  Liquid helium

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- Session 2 - Fluid Acquisition and Transfer

  Liquid acquisition techniques and devices
  Transfer line and tank chilldown
  Fill techniques and procedures
  Liquid slosh
  Mass gauging
  Modelling of cryogen in low gravity
  Fluid mixing and temperature destratification

- Session 3 - Fluid Management Applications

  Solar space power systems
  Nuclear space power systems
  Thermal management systems
  Environmental control and life-support systems

- Session 4 - Project Activities and Insights

  Shuttle get-away-special fluid acquisition and gauging experiment
  Shuttle middeck locker fluid transfer experiment
  Space experiment development activities and process

The individual technical presentations are summarized in this publication.

CONTENTS

Page

Foreword iii

Preface v

Symposium Overview
James Romero, NASA Headquarters 1

SESSION I - FLUID STORAGE
Chairman: Myron E. Hill, NASA Lewis Research Center

Advanced Long Term Cryogenic Storage Systems
Norman S. Brown, NASA Marshall Space Flight Center 7

Long Term Cryogenic Storage Facility Systems Study
John R. Schuster, General Dynamics Space Systems Division 17

Space Station Experiment Definition: Long Term Cryogenic Fluid Storage
David H. Riemer, Beech Aircraft Corporation 31

Helium Technology Issues
Peter Kittel, NASA Ames Research Center 43

SESSION II - FLUID ACQUISITION AND TRANSFER
Chairman: John C. Aydelott, NASA Lewis Research Center

Overview - Fluid Acquisition and Transfer
Jere S. Meserole, Boeing Aerospace Company 57

The Coupled Dynamics of Fluids and Spacecraft in Low Gravity and
Low Gravity Fluid Measurement
R. John Hansman, Lee D. Peterson, and Edward F. Crawley
Massachusetts Institute of Technology 67

Numerical Modelling of Cryogenic Propellant Behavior in Low-G
John I. Hochstein, Washington University 85

Mixing-Induced Fluid Destratification and Ullage Condensation
Jere S. Meserole and Ogden S. Jones, Boeing Aerospace Company
Anthony F. Fortini, Anthony Enterprises 101

Cryogenic Fluid Management Flight Experiment (CFMFE)
David M. DeFelice, NASA Lewis Research Center 119

Superfluid Helium on Orbit Transfer (SHOOT)
Michael J. DiPirro, NASA/Goddard Space Flight Center 125

SESSION III - FLUID MANAGEMENT APPLICATIONS
Chairman: Jerry M. Winter, NASA Lewis Research Center

Space Station Power Systems
John F. Cassidy, NASA Lewis Research Center 137

Microgravity Fluid Management in Two-Phase Thermal Systems
A NASA JSC Perspective
Richard C. Parish, NASA Johnson Space Center 139

Microgravity Fluid Management Requirements of Advanced Solar
Dynamic Power Systems
Robert P. Migra, Sverdrup Technology, Inc. 151

Two-Phase Reduced Gravity Experiments for a Space Reactor Design
Zenen I. Antoniak, Battelle - Pacific Northwest Laboratory 163

Maintenance Evaluation for Space Station Liquid Systems
Charles Flugel, Hamilton Standard 171

SESSION IV - PROJECT ACTIVITIES AND INSIGHTS
Chairman: Richard W. Vernon, NASA Lewis Research Center

Space Experiment Development Process
James F. DePauw, NASA Lewis Research Center 189

Shuttle Get-Away Special Experiments
George Orton, McDonnell Douglas Corporation 201

Shuttle Middeck Fluid Transfer Experiment - Lessons Learned
James Tegart, Martin Marietta Aerospace 217

SYMPOSIUM OVERVIEW

James Romero
NASA Headquarters
Washington, DC

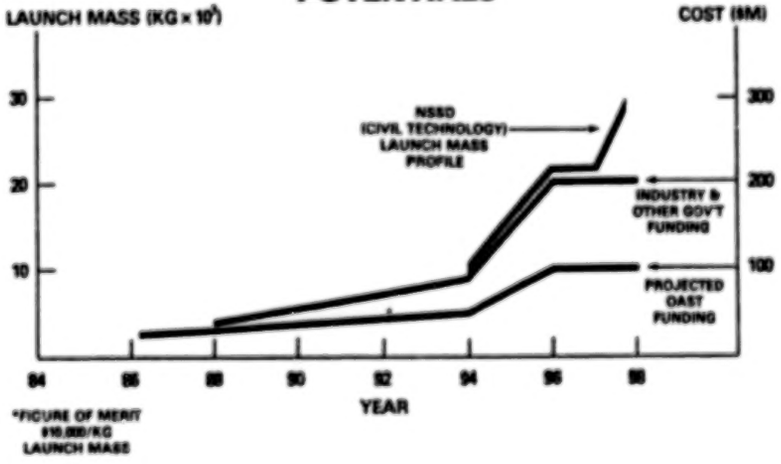
INDUSTRY/UNIVERSITY EXPERIMENTS PROGRAM (OUTREACH)

- STATUS
  - CBD ANNOUNCEMENT RELEASED - JUNE 30
  - RFP RELEASE - AUG. 15
- OBJECTIVE
  - PROVIDE INCENTIVES TO INDUSTRY TO BETTER UTILIZE TECHNOLOGY DEVELOPMENT POTENTIAL OF SPACE
- APPROACH
  - SELECT EXPERIMENTS OF MUTUAL BENEFIT TO INDUSTRY AND NASA
  - JOINTLY DEVELOP, PROGRAM, AND FUND APPROPRIATE EXPERIMENTS
  - PROVIDE UNIQUE FACILITY (SHUTTLE OR SPACE STATION)

CIVIL SPACE TECHNOLOGY INITIATIVE

FOCUSED THRUSTS
TO REMEDY GAPS
IN TECHNOLOGY BASE
TO ENABLE HIGH PRIORITY PROGRAMS

IN-SPACE EXPERIMENT PROGRAM POTENTIALS



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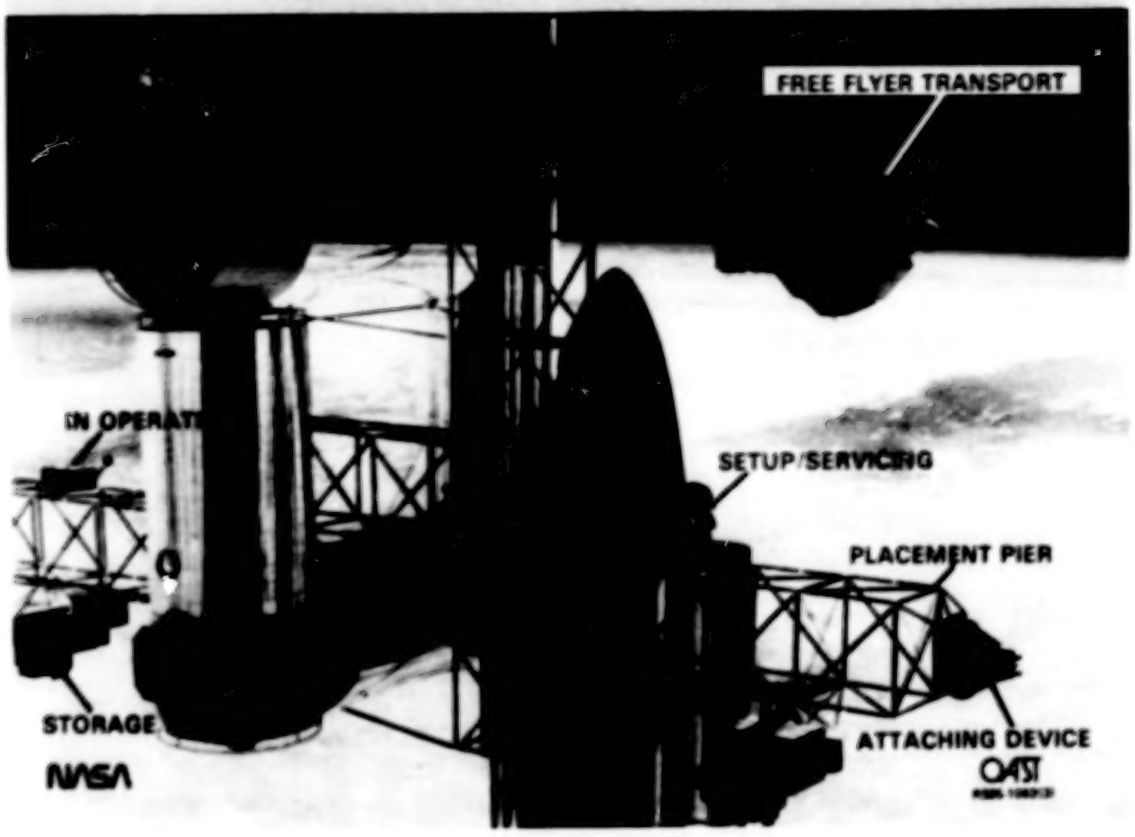
TECHNOLOGY EXPERIMENTATION



IN-SPACE R & T APPROACH

- ESTABLISH OAST AS NATIONAL FOCAL POINT FOR IN-SPACE R&T
- COORDINATE USER COMMUNITY REQUIREMENTS AND PLANS
  - WORKSHOPS
  - SYMPOSIA
- STIMULATE COOPERATIVE VENTURES
  - OUTREACH
  - GUEST INVESTIGATOR

IN-SPACE R & T GOAL

- DEVELOP AN IN-SPACE R&T PROGRAM, UTILIZING THE SPACE STATION FACILITY AS A LOGICAL COMPLEMENT TO GROUND-BASED R&T
  - DEMAND FOR NEW SPACE TECHNOLOGIES IS REAL
  - TECHNOLOGY DEVELOPMENT AND USE WILL BE ENHANCED BY KNOWLEDGE AND CONFIDENCE GAINED THROUGH EXPERIMENTS AND DEMONSTRATIONS CONDUCTED IN THE SPACE ENVIRONMENT

IN-SPACE TECHNOLOGY EXPERIMENTS

AN EXPONENTIALLY EXPANDING PROGRAM DRIVEN BY THE CONVERGENCE OF:

USER NEEDS	&	SPACE FACILITIES
• RESEARCH - MATERIALS - FLUIDS - DEVICES - STRUCTURES, CONTROLS • DEMONSTRATION - PROOF OF CONCEPT - ENGINEERING DEMO - FLIGHT QUALIFICATION		• SHUTTLE - PAYLOAD BAY - MID-DECK - CANNISTERS - HITCHHIKERS • SPACE STATION - INTERNAL PAYLOADS - EXTERNALLY MOUNTED - TECHNOLOGY LAB. MODULE - PLATFORM BASED

CSTI LOGIC

- RESTORE AGENCY TECHNICAL STRENGTH
- FOCUSED TECHNOLOGY DEMONSTRATIONS
- MEETS PRIORITY NEEDS...NASA...NATIONAL SECURITY
- REBUILD IMAGE...MORALE...SKILLS
- AFFORDABLE

CSTI FOCUSED THRUSTS

ENABLE LOW-COST ACCESS TO SPACE

- LAUNCH VEHICLE PROPULSION
- BOOSTER TECHNOLOGY
- SPACE BASED PROPULSION
- LAUNCH SYSTEM AUTONOMY
- AEROBRAKING TECHNOLOGY

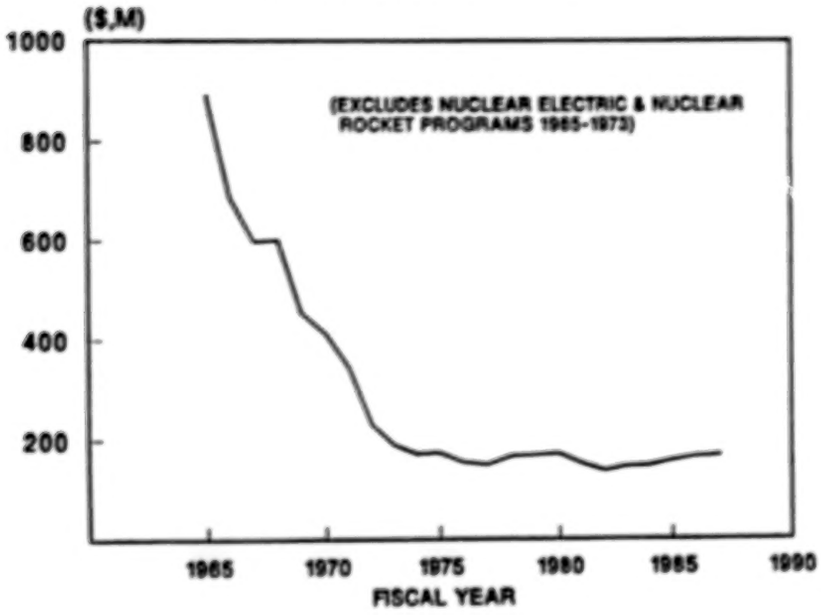
ENABLE NASA MISSIONS

- HIGH CAPACITY POWER
- SPACECRAFT POWER
- AUTOMATION & ROBOTICS
- LARGE STRUCTURES & CONTROL
- SENSOR DEVICE TECHNOLOGY
- HIGH DATA RATE SYSTEMS

A MEANS TO MANY ENDS

SPACE R & T FUNDING TREND

(CONSTANT FY 87 DOLLARS)



STATE OF TECHNOLOGY

- TECHNOLOGY BASE IS DEFICIENT
  - LIVING OFF PAST
  - TECHNOLOGY NO LONGER LEADS WITH SOLUTIONS... IT CHASES PROBLEMS
- EXPECTATIONS EXCEED WHAT TECHNOLOGY CAN DELIVER
- U.S. LEADERSHIP CHALLENGED
- DECLINE OF NASA EXPERTISE

NASA SPACE EMPHASIS

- RECONSTITUTE SHUTTLE CAPABILITY
- MAINTAIN SPACE STATION MOMENTUM
- RESOLVE SCIENCE MISSION BACKLOG

AND

- REBUILD TECHNOLOGY BASE

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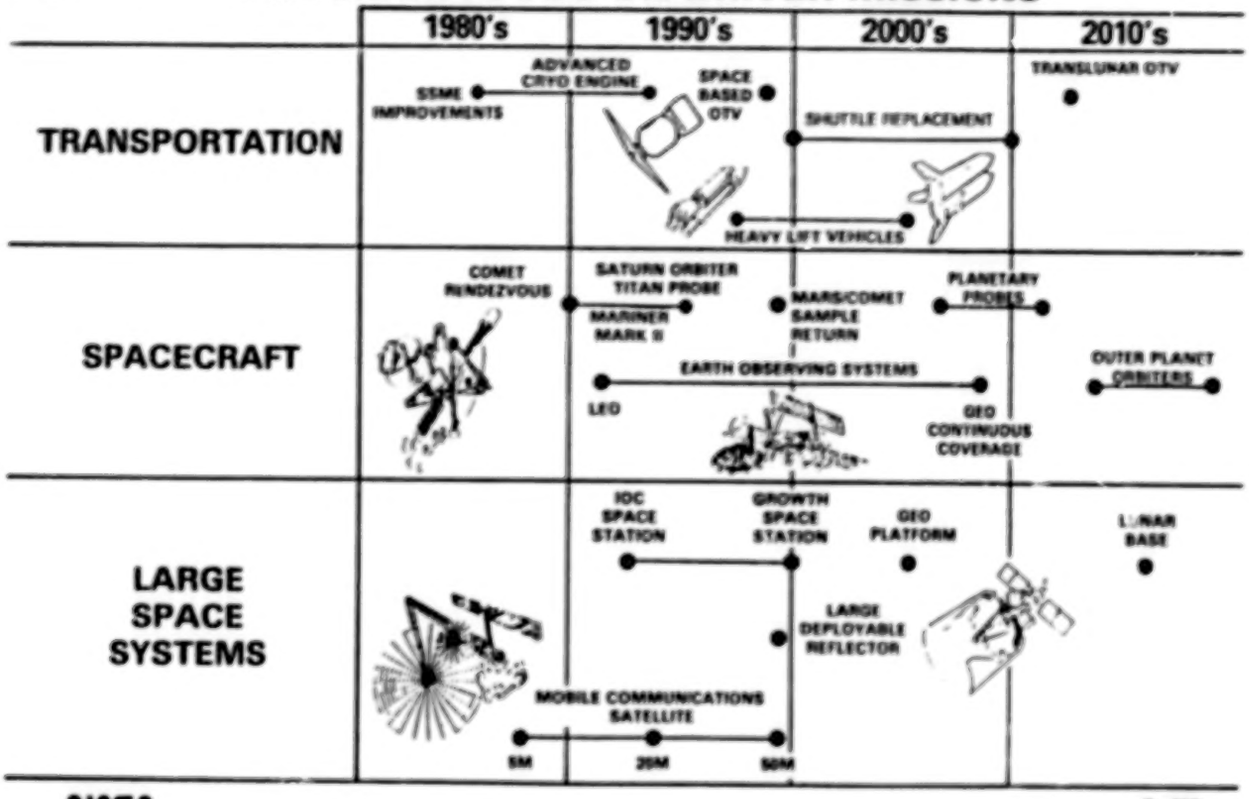
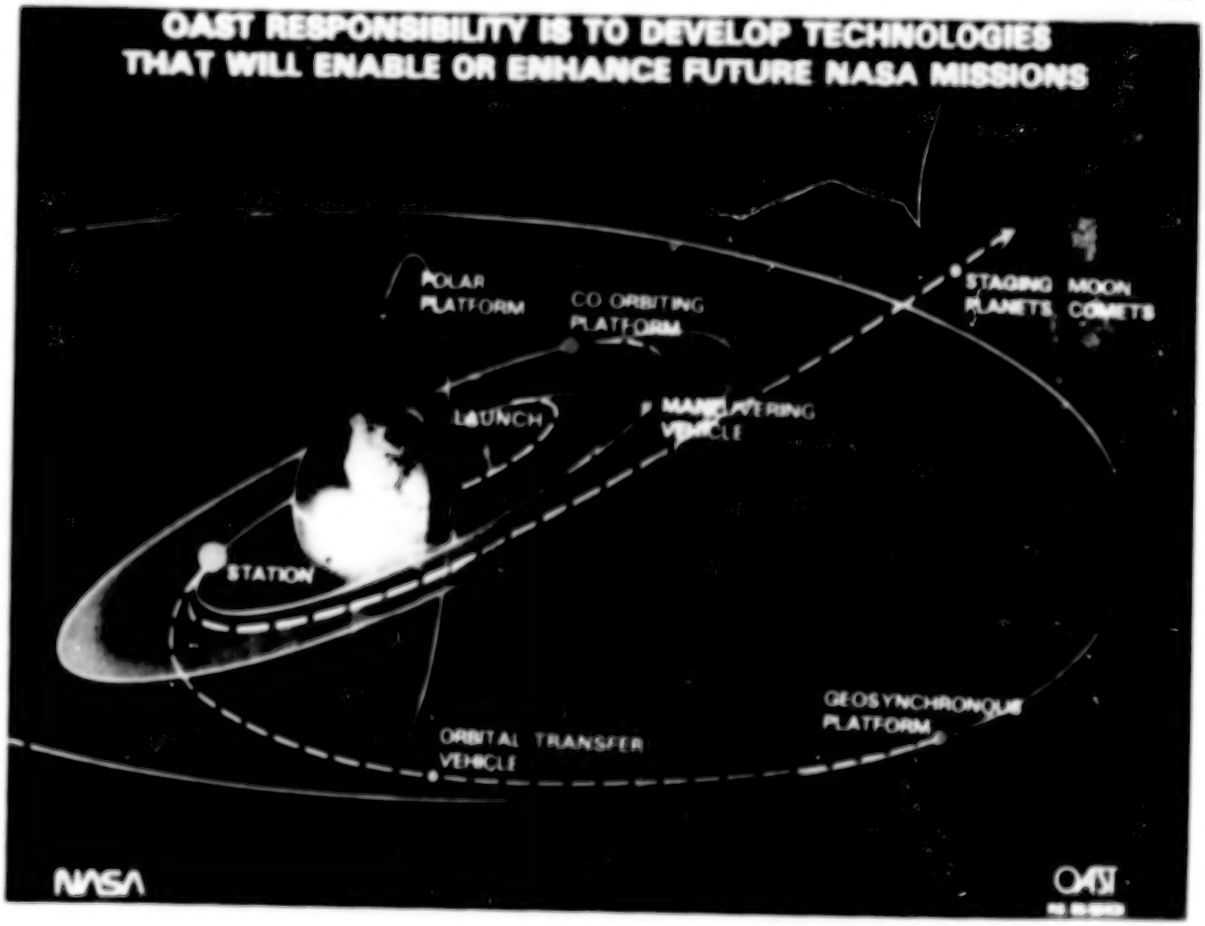
PROGRAM FOCUS ON DRIVER MISSIONS



NASA

OAST

OAST RESPONSIBILITY IS TO DEVELOP TECHNOLOGIES
THAT WILL ENABLE OR ENHANCE FUTURE NASA MISSIONS



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ADVANCED LONG TERM CRYOGENIC STORAGE SYSTEMS

Norman S. Brown
NASA Marshall Space Flight Center
Marshall Space Flight Center, Alabama

Long term, cryogenic fluid storage facilites will be required to support future space programs such as the space-based Orbital Transfer Vehicle (OTV), Telescopes, and Laser Systems. An orbital liquid oxygen/liquid hydrogen storage system with an initial capacity of approximately 200,000 LB will be required. The storage facility tank design must have the capability of fluid acquisition in microgravity and limit cryogen boiloff due to environmental heating. Cryogenic boiloff management features, minimizing earth-to-orbit transportation costs, will include advanced thick multilayer insulation/integrated vapor cooled shield concepts, low conductance support structures, and refrigeration/reliquefaction systems. Contracted study efforts are underway to develop storage system designs, technology plans, test article hardware designs, and plans for ground/flight testing.

INTRODUCTION:

Advanced, long term orbital cryogenic storage systems (Figure 1)include thick multilayer insulation (MLI)/integrated vapor cooled shields (VCS), low conductance support structures, and reliquefaction systems. An orbital storage system should be designed for safety, reliability, and long term thermal performance. Passive cryogenic fluid storage and active cryogenic boiloff management, or a combination of both, are being studied to determine the optimum system design.

FIGURE 1.

SYSTEM DESCRIPTION:

An orbital cryogenic storage facility system will rely on the long term performance of various subsystems (Figure 2). Cryogenic fluid boiloff management features will include the following:

Thick multilayer insulation (MLI) systems consist of thin radiation shields (metallized polymeric film) separated by low-conducting spacer materials (Dacron, Nomex, nylon). Cryogenic storage will require multiple layers of MLI with fabrication/assembly techniques that minimize seam heat leaks.

The design of a vapor cooled shield (VCS) resembles a dual pass heat exchanger. Assuming liquid hydrogen/liquid oxygen (LH_2/LO_2) the VCS is most effective when using a thermodynamically coupled tank configuration. Saturated vapor (boiloff) is removed from the LH_2 tank and routed in the VCS around the tank to intercept heat leaks. After the vented fluid leaves the LH_2 tank VCS, it is routed to the LO_2 tank VCS to perform the same heat leak intercept function.

The thermodynamic vent system (TVS) performs a dual function. The primary function is to regulate tank pressure through controlled escape of saturated vapor (boiloff). Additionally, when used in conjunction with a VCS, the TVS provides the saturated vapor from the liquid storage tank.

LONG TERM CRYOGENIC STORAGE FACILITY
100,000 LB_M LH_2/LO_2 CAPACITY

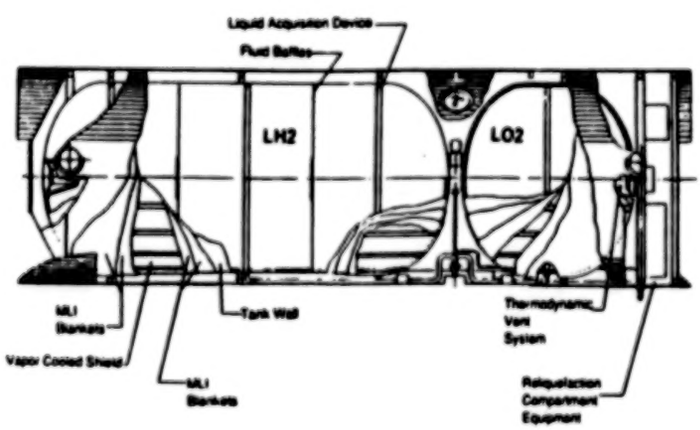

FIGURE 2.

Tank support struts are a key element in the thermal design of a cryogenic storage system. Various composite materials with high strength and low conductivity properties are under investigation for use as support structures. Other options include configurations of orbital disconnect struts where highly efficient struts are complimented by larger struts for support during launch loads.

A reliquefaction system would be designed to reliquefy the boiloff of propellants. Reliquefaction would eliminate the need for any external system venting of saturated vapor. Reliability, along with power, weight, and volume requirements are areas of development for space based reliquefaction systems.

Propellant storage conditions should be optimized with respect to safety, complexity, and cost. On orbit storage of propellant at lower than normal (15-20 psia) saturation pressures will allow thin walled tanks resulting in weight savings. However, to operate at reduced tank pressures (approximately 5 psia) thermal conditioning of delivered propellant is required. The least complex method of propellant delivery to orbit is in the 15-20 psia saturation pressure range due to ground handling and stress loading on the tanks during ascent. The delivered propellant would then require on-orbit thermal conditioning if the facility storage pressure is less than the 15-20 psia. Figure 3 shows the amount of energy removal required per pound of LH_2 starting at 20 psia going to a 'conditioned' 5 psia. Figure 4 relates the reliquefaction power required to perform the 'conditioning' for various LH_2 quantities. Judging from the energy requirements, storage conditions at pressures of 15-20 psia, assuming commonality between users, are required. The case for LO_2 conditioning is similar.

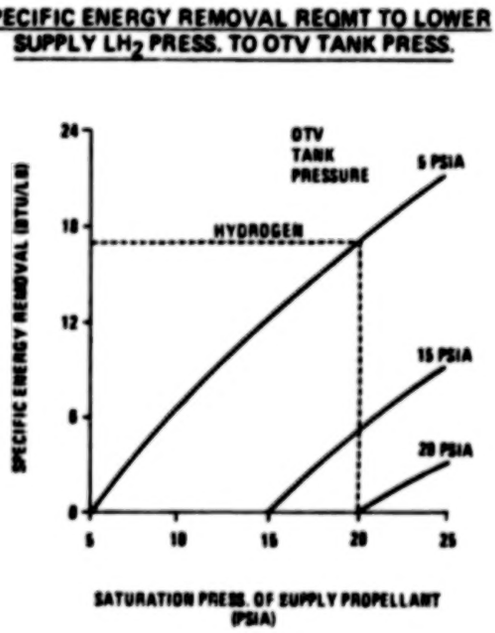

FIGURE 3.

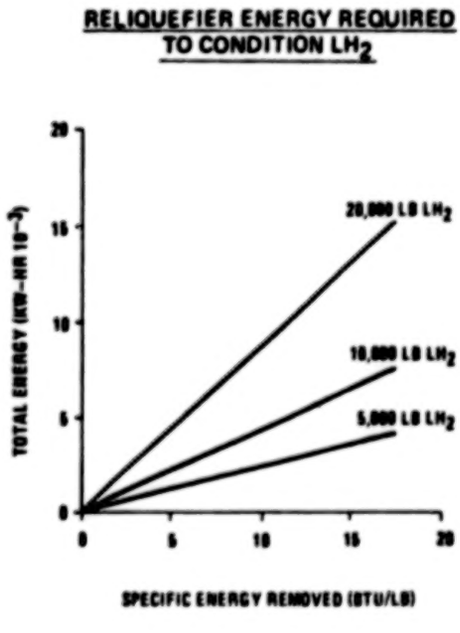

FIGURE 4.

A subsystem of a long term storage facility is the VCS. In Figure 5, the effect of adding a VCS to the LH_2 tank is shown. The parametric data is based on a 100,000 lb LH_2/LO_2 facility. The trend established shows a greater than fifty percent (50%) reduction in LH_2 boiloff due to the addition of the VCS. The distance the VCS is located from the tank wall has an effect on the LH_2 boiloff (Figure 6). With 4 inches of MLI, a 10 percent reduction in boiloff can be achieved by locating optimally the VCS (2 inches from the tank wall).

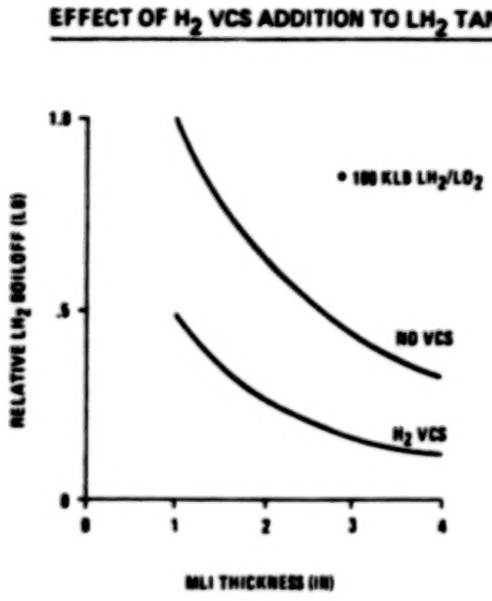

FIGURE 5.

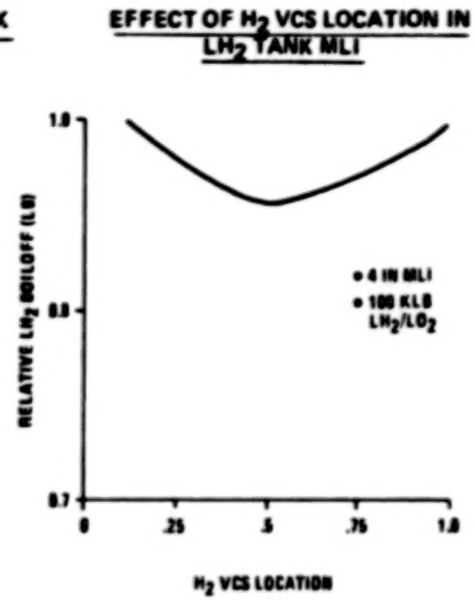

FIGURE 6.

A dual VCS H_2 system on the LH_2 tank can improve the thermal performance by 40 percent over a single VCS. Figure 7 shows the results of varying the locations of the two shields on the hydrogen tank. The curves suggest that the preferred locations for the inner and outer shields are 30 and 66 percent of the distance from the tank wall to the outer insulation surface. Figure 8 shows the effect of varying the H_2 VCS location on the oxygen tank. Approximately 75 percent of the distance from the LO_2 tank wall results in the lowest LO_2 boiloff.

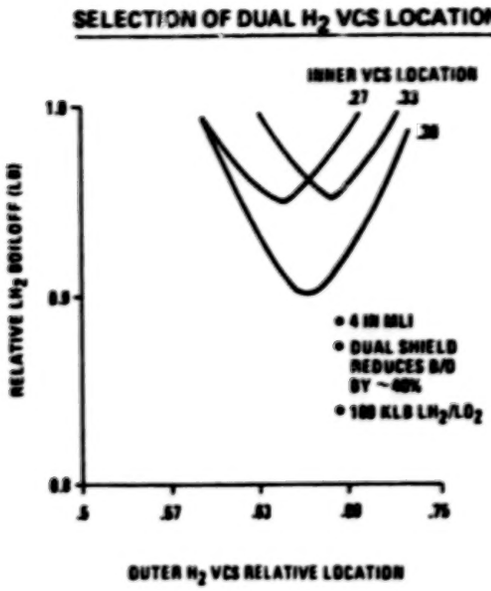

FIGURE 7.

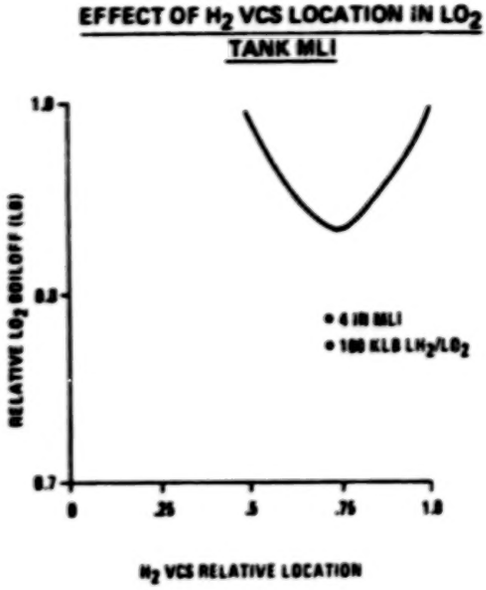

FIGURE 8.

A para-ortho hydrogen converter exploits the endothermic reaction of transforming para hydrogen into a para-ortho mixture. As saturated hydrogen vapor (boiloff) exits the LH_2 tank VCS, it is approximately 100 percent para. However, prior to entering the LO_2 tank VCS a catalyst bed speeds up the natural para-ortho conversion process and yields a para-ortho mixture. The conversion to the higher energy state absorbs energy and results in approximately a 40 percent increase in the hydrogen heat capacity (Figure 9). Therefore, the hydrogen vapor temperature in the VCS is reduced resulting in approximately 10 percent savings in LO_2 boiloff (Figure 10).

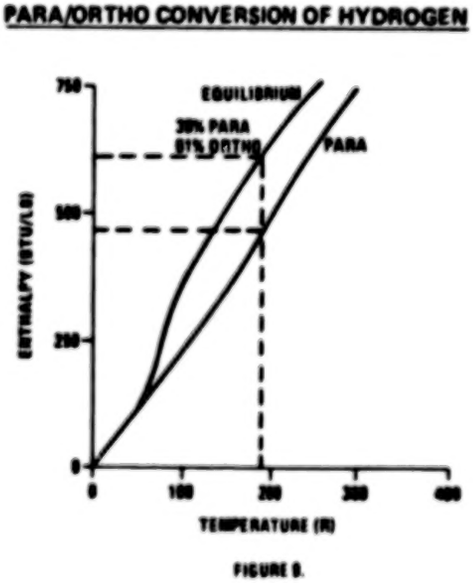

FIGURE 9.

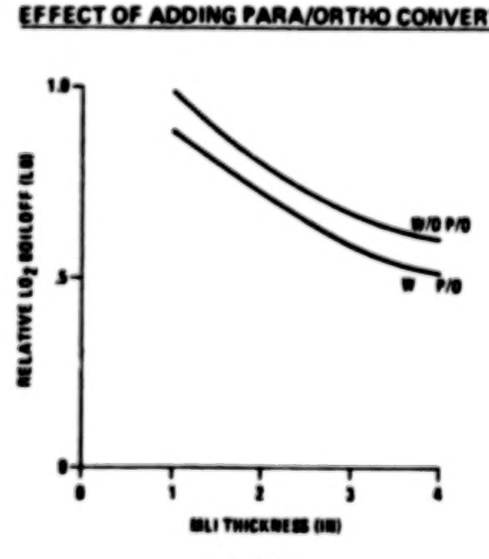

FIGURE 10.

A cryogenic reliquefaction system must meet the long requirements of safety, reliability, performance, and cost. Several refrigeration cycles are currently under development to meet future design criteria. Table 1 identifies characteristics of some of the more established cycles currently under development. Figures 11 and 12 plot critical parameters of the refrigeration cycles discussed below.

The Stirling refrigerator has been developed for long life performance utilizing magnetic bearings to suspend the reciprocating compressor and expander. This 2 stage system has demonstrated the potential for reliable operation and has good power utilization efficiency.

TABLE 1

SURVEY OF SMALL, LONG-LIFE REFRIGERATORS

CYCLE	MANUFACTURER	RATED TEMP. (°K)	CAPACITY (W/@T)	POWER INPUT (WATTS)	VOL. (ft^3) / WEIGHT (lb_m)	HOURS TO DATE	LIFE LIMITING COMPONENT	DEVELOPMENT STATUS	COMMENTS
STIRLING (SPRING SUSPENDED)	RUTHERFORD APPLETON LAB'S OXFORD	80°K	1 W	60	-- / 11 LB W/O ELECT.	6,000	UNKNOWN	LIFE TESTING	VERY SIMPLE AND LIGHTWEIGHT
STIRLING (MAGNETICALLY SUSPENDED)	PHILIPS	65°K (40-110)	5 W (0 - 10)	220	(40x10x10) / 2.31 ft^3	SYSTEM; 6500 MECH PARTS, 10,000	ELECTRONICS IN DC-DC CONVERTER	MECHANICAL TESTS TO 10,000 HOURS (ELECTRONICS TO 2500 HRS & IMPROVING)	ADDITION OF MAG. BRGS. MAKES LONG UNATTENDED OPERATION POSSIBLE. (2-STAGE UNDER DEVELOPMENT)
B^3 BRAYTON (2-STAGE)	A.D. LITTLE	12,60	1.5 @ 12K 40 @ 60K	2670	17.4 / 665	7,000 (MECHANICAL COMPONENT TESTS)	EXPANDER	3-STAGE UNIT UNDER DEVEL. @ WEIGHT; LARGER CAPACITY	GAS BEARINGS PROBLEMS WITH EXPANDER @ 7000 HR
TURBO-BRAY (2-STAGE)	GARRETT-AIRESEARCH	70, 90	20 W @ 70, 90K	5,000	22 / 390	-	FOIL SUPP. GAS BEARINGS	FOIL/GAS BEARING RELIABILITY & He GAS RETENTION	INFORMATION ON REFRIG. TEMPERATURE IS CLASSIFIED AND UNAVAILABLE FOR LATEST MODEL
WILLEMIER	HUGHES	10,14,64	.15 @ 10K 1.9 @ 14K 8.3 @ 64	2100	5 / 101	31,000	MECHANICAL (PISTONS/CYL WEAROUT)	CURRENTLY DEVEL. LOW WEAR SEALS & RIDERS FOR LONG WEAR - MAKE UP GAS ALSO A PROBLEM	YEARS OF EXPER. IN FIELD FOR TACTICAL APPLICATIONS
MOLECULAR ADSORPTION	J.P.L.	27	0.05W	-	-	300	-	BREADBOARD TEST 3-UNIT LoH$_2$	NEED HIGH PRESS. COMPRESSOR & HEAT INPUT (& 77K INT. STG. COOLING)
MAGNETIC	ASTRONAUTICS & LASL	20, 90	20 @ 20K 70 @ 90K	900 W	34 / 1,027	N/A	-	CONCEPTUAL	CONCEPTUAL DESIGN ONLY (SHOULD ACHIEVE 30 - 50% CARNOT)

There are two refrigeration systems under development utilizing Brayton cycles, the gas bearing rotary-reciprocating-refrigerator (R^3) and the turbo-Brayton. The R^3 has gas rotating bearings and a reciprocating compressor. This unit has the potential for long life, low wear, and reliable performance. The turbo-Brayton utilizes turbomachinery in a two stage expansion reversed cycle.

Vuilleumier refrigerators are basically Stirling cycles which utilize high temperature heat to drive the compression stage. These machines have accumulated many test hours.

Molecular adsorption refrigerators are in the development stages. Gaseous hydrogen is pumped at high pressure through heat exchangers and then expanded (using a Joule-Thomson valve) over a intermetallic hydride bed for cooling. The only moving parts of the system are self-regulating check valves.

Magnetic refrigeration is also in the early development stage. Materials that increase and decrease in temperature when alternately placed in a magnetic field drive this cycle. Such a system could be efficient, however many practical problems exist.

REFRIGERATOR POWER INPUT VS CAPACITY

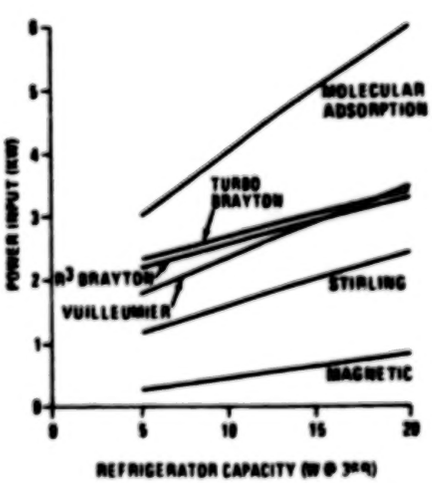

FIGURE 11.

REFRIGERATOR SYSTEM WT. VS. CAPACITY

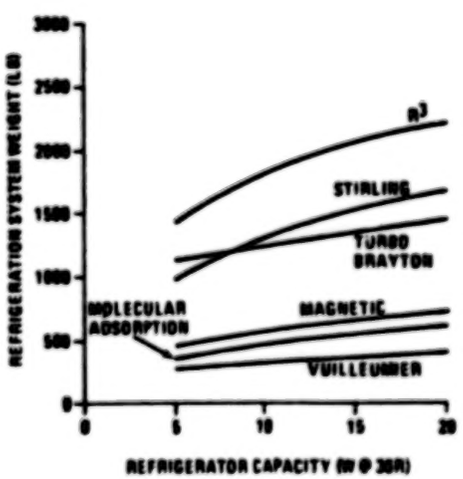

FIGURE 12.

Operational safety requirements will be a major factor in an orbital storage facility design. Various mission phases must be analysed with respect to hazard potential: Pre-launch (ground processing), launch, STS abort, and space based operations (propellant transfer, venting). Sensor and valve redundancies, meteroid bumpers, pressure/propellant tank structural structural margins, LH_2/LO_2 vents/disconnects separation distances, and electrical grounding are all design requirements of a storage facility. Table 2 outlines mission phases and potential hazards/solutions associated with each.

TABLE 2

HAZARD ANALYSIS

STS ABORT

- N/A – TANKS ARE LAUNCHED DRY

OPERATIONAL

- CRYOGENIC LEAKAGE
  - METEROID/DEBRIS SHIELDING TO PREVENT PUNCTURE
  - "ZERO-LEAK" CONNECTORS
  - VENT TRANSFER LINES/PURGE AFTER TRANSFER OP.
  - MAN RATED REDUNDANT FAIL OP/SAFE ON CRITICAL SYSTEMS (IF LOCATED @ MAN TENDED FACILITY)
- TANK OVERPRESSURIZATION
  - SUFFICIENT PRESSURE RELIEF VALVES (SIZE & LOCATION)
  - TANK SHOULD HAVE SUFFICIENT STRUCTURAL MARGINS 'LEAK BEFORE BURST'
- CRYOGEN CONTAMINATION
  - RELIEF VALVES W/PROTECTION TO PREVENT CONTAMINANTS

SPACE STATION ABORT

- SUFFICIENT PRESSURANT FOR LIQUID DUMP (ONE TANK)
- TANK HEATERS TO BOILOFF

SUMMARY:
A long term orbital storage facility will require several precursor 'experiments' in order to demonstrate system performance. Currently, the need exists for a multiphased technology demonstration program. The Cryogenic Fluid Management Facility (CFMF) experiment is planned for 1992 to demonstrate the areas of fluid transfer, mass gauging, and fill operations. A cryogenic storage experiment (short term test) is required as a precursor to long term Space Station testing. System performance (refrigerator, MLI/VCS) must be validated for withstanding launch loads and still performing on-orbit. Prior to facility IOC, a long term orbital system test would assure the necessary confidence in the storage design to begin space basing operations. Figure 13 summarizes the storage facility evolution. Table 3 is a partial listing of major programs supporting the technology requirements of long term orbital storage of cryogens.

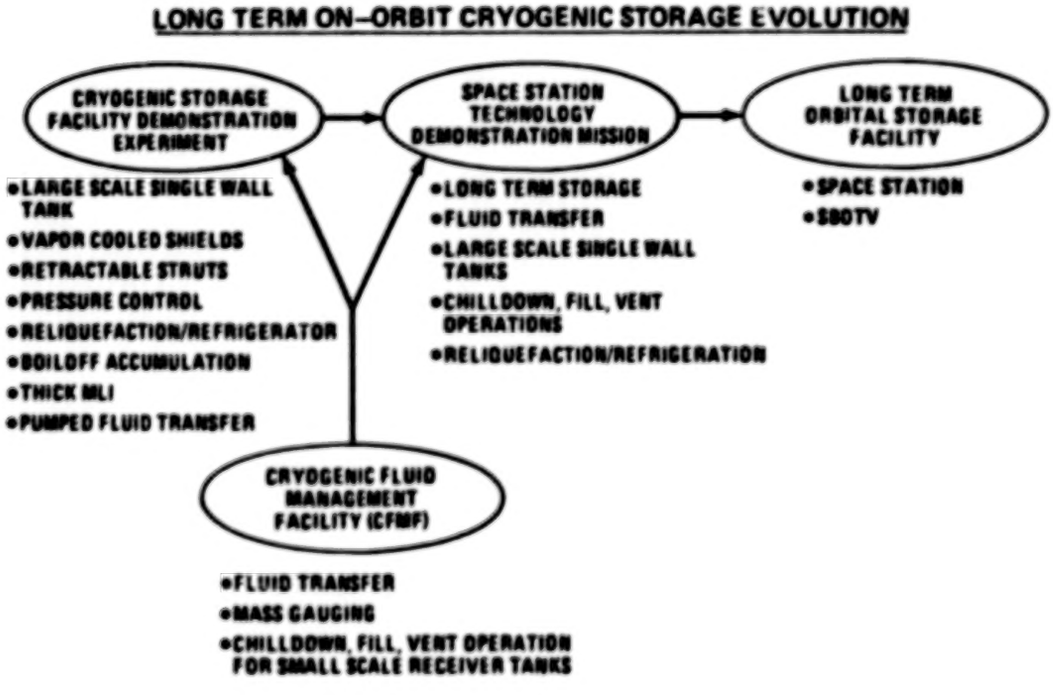

FIGURE 13.

TABLE 3

RELATED EFFORTS
(PAST AND ONGOING ACTIVITIES)

•THICK MULTILAYER INSULATION	AFRPL
•ADVANCED ORBIT – ORBIT VEHICLE STUDIES OTV, MOTV	MSFC
•ADVANCED CRYOGENIC TANK STRUCTURES	LaRC MSFC
•ADVANCED THERMAL PROTECTION SYSTEMS	LaRC MSFC JSC LRC
•CRYOGENIC INSULATION CRYOGENIC BREADBOARD (MSFC)	MSFC LRC LaRC
•PROPELLANT MANAGEMENT SYSTEMS CRYOGENIC BREADBOARD (MSFC)	MSFC JSC LRC
•CRYOGENIC FLUID MANAGEMENT FACILITY (CFMF)	LRC
•LONG TERM CRYOGENIC STORAGE STUDIES	MSFC LRC
•CRYOGENIC REFRIGERATOR DEVELOPMENT	JPL

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LONG TERM CRYOGENIC STORAGE FACILITY SYSTEMS STUDY

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The LTCSFSS is a Phase A study of a large capacity orbital propellant depot for the space based, cryogenic orbital transfer vehicle. The study is being performed for Marshall Space Flight Center by General Dynamics Space Systems Division and has five principal objectives:

1) Definition of preliminary concept designs for four storage facility concepts

2) Selection of preferred concepts through the application of trade studies to candidate propellant management system components

3) Preparation of a conceptual design for an orbital storage facility

4) Development of supporting research and technology requirements

5) Development of a test program to demonstrate facility performance

The initial study has been completed, and continuation activities are just getting underway to provide greater detail in key areas and accommodate changes in study guidelines and assumptions.

A total of eighteen major trade studies were performed, leading to the selection of both an all-passive concept and a total reliquefaction concept for managing cryogen boiloff. The all-passive concept may be preferred if the facility is located on a free-flying platform; the total reliquefaction concept may be preferred if its located on the Space Station.

Eighteen enabling technology needs were identified and task plans prepared along with cost and duration estimates. They total about $12 million and range from two to six years duration.

Several testing options were identified for reducing the technical risk associated with fielding the orbital propellant depot. On the bases of risk reduction, schedule compatibility and cost, an option was selected that involves performing a short term orbital flight experiment in the Orbiter cargo bay with a subscale, integrated hydrogen storage and transfer system.

The four propellant storage concepts are very similar: all route hydrogen boiloff through vapor-cooled shields (VCSs) on the hydrogen and oxygen tanks. Concepts 1, 2 and 3 store both hydrogen and oxygen boiloff in high pressure accumulators, whereas Concept 4 reliquefies all boiloff and returns it to the tanks. Concept 2 has an additional shield that is connected to a refrigerator. Concepts 1, 2 and 3 use high pressure accumulated oxygen boiloff for oxygen tank autogenous pressurization during OTV tanking. Concept 4 uses a liquid pump and heat exchanger to provide autogenous oxygen pressurization. Concept 3 is the only concept using high pressure accumulated hydrogen for hydrogen tank autogenous pressurization. The other concepts use a pump and heat exchanger.

CONCEPT SCHEMATICS

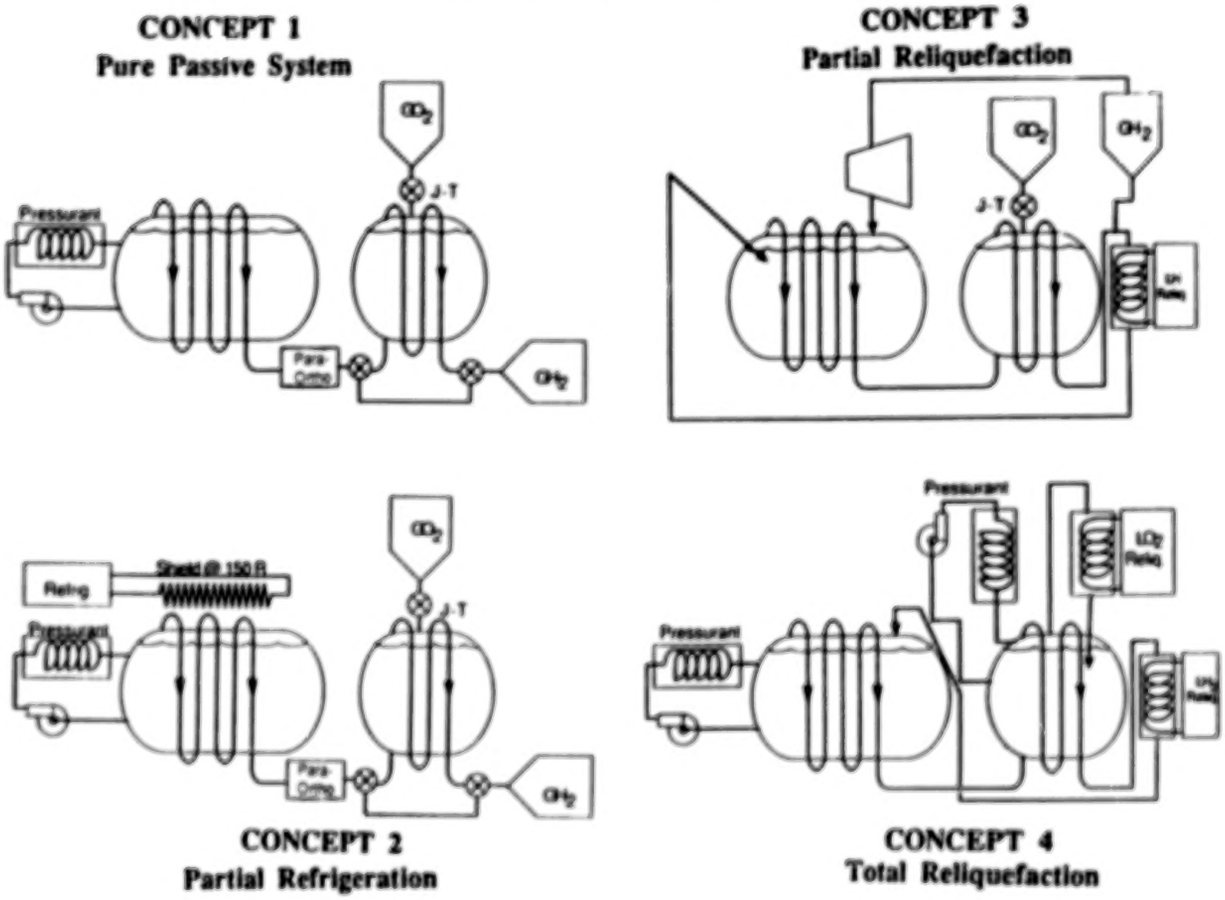

Figure 1

Eighteen trade studies were performed at the subsystem and component levels, leading to the selection of preferred approaches and overall system concepts. The system consists of two 100,000 lb capacity tank sets attached to the windward side of the growth Space Station. Passive thermal features to limit tank heating include 4 inches of multilayer insulation, hydrogen vapor-cooled shields surrounding both hydrogen and oxygen tanks, and permanent low conductance composite struts. The external cover around the tank set is periodically changed as the solar coating degrades. Tank liquid is acquired in microgravity using a screen channel capillary device and transferred using autogenous tank pressurization and liquid pumps. Tank pressure is controlled with a thermodynamic vent system. OTV tanks are preconditioned using a charge/hold/vent cycle and then filled without venting. Refrigerator and reliquefaction systems are based on the magnetic suspension free piston Stirling refrigerator. Micrometeoroid and debris protection will be provided by an inner structural shell to which the tank support struts are attached and by a thin outer bumper. The tank sets will be launched dry and will store propellants at a pressure of 20 psia. Boiloff that is not reliquefied will be stored in high pressure accumulators and periodically transported away by the OMV for venting.

TRADE STUDIES

TRADE	RESULT
System layout	Two 100 klb tanksets attached to Space Station
Tank configuration	Cylindrical, 2219 aluminum alloy tanks
Passive insulation configurations	4 inches of coated DAK/Dacron net
Structural support schemes	Permanent composite struts (<.05Qtot)
VCS configurations	Hydrogen shields on both tanks
Thermal coating degradation effects	Periodically change solar cover
Fluid acquisition systems	Screen channel capillary LAD
Pressure control systems	Thermodynamic vent systems on both tanks
Fluid transfer options	Autogenous pressurization & liquid transfer pumps
System thermal preconditioning requirements	Use charge/hold/vent and no-vent fill
Refrigeration/reliquefaction systems	Magnetic Stirling refrigerator
Operational/safety requirements	Safety waivers required
Propellant loading/unloading requirements	Pump and heat exchanger for tanker pressurization
Instrumentation and controls	Mass gauging and two-phase flowrate are developmental
Micrometeoroid/debris protection	Cylindrical shell with outer bumper
Launch condition	Launch tank set empty and warm
Boiloff storage and utilization	High pressure storage, OMV transport & vent
Propellant storage condition	20 psia least facility cost; 5 psia best obtained by ground conditioning

Figure 2

Each tank set contains 100,000 lb of propellants. The diameters of each are 14.5 ft in order to fit in the Orbiter cargo bay. The lengths of Concepts 2, 3 and 4 are 50.0 ft while Concept 1 is 53.5 ft long. The dry weight of Concept 1 is 27,800 lb with the other concepts being 3,300 to 3,980 lb heavier. The hydrogen and oxygen loss rates and electrical energy use depend on the thermal insulation system features. Estimates for each concept assume 4.0 in. total MLI thickness, and that a hydrogen VCS is used for both the hydrogen and oxygen tanks. Concepts 1 and 2 employ a para/ortho catalytic converter in the hydrogen vapor line between the two vapor-cooled shields, and Concept 2 has a refrigeration shield outboard of the VCS on the hydrogen tank.

None of the concepts have any net oxygen loss since Concepts 1, 2 and 3 allow just enough boiloff to provide the accumulated oxygen for tank pressurization during OTV tanking. Concept 4 reliquefies the oxygen boiloff. Concepts 1 and 2 have 315 and 207 lb/month, respectively, of accumulated high-pressure hydrogen boiloff that must be discarded.

Concept 4, the total reliquefaction concept, requires an average power of about 2 kW to run the reliquefaction system. Concept 3 requires 3,570 kWh/month of electrical energy, most of which is used to run the hydrogen reliquefaction system. This concept suffers excessive hydrogen boiloff because it uses stored hydrogen boiloff for pressurization during OTV tanking. The high boiloff is caused by the enthalpy of superheat of the pressurant, which thermally equilibrates with liquid in the tank during the approximately two-hour OTV tanking operation. Its other negative effect is that the rising tank saturation pressure caused by thermal equilibration increases the pressure of the tanked OTV hydrogen, requiring heavier hydrogen tankage on the OTV.

CONCEPT SUMMARY

	Concept 1	Concept 2	Concept 3	Concept 4
Boiloff management method	Passive	Refrig.	Partial Reliq.	Total Reliq.
Propellant capacity (kg)	45,400	45,400	45,400	45,400
Diameter (m)	4.42	4.42	4.42	4.42
Length (m)	13.3	15.2	15.2	15.2
Dry weight (kg)	12,600	14,400	14,300	14,100
MLI thickness (mm)	102	102	102	102
Coupled VCS	Yes	Yes	Yes	Yes
Refrigeration shield	No	Yes	No	No
Para/ortho converter	Yes	Yes	No	No
Hydrogen loss, (kg/mo)	143	93.9	0	0
Oxygen loss (kg/mo)	0	0	0	0
Electrical energy use (kWh/mo)	146	365	3,570	1,430
(Pumps & Compressor kWh/mo)	146	111	226	17
(Refrigeration kWh/mo)	0	254	3,344	1,414

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Figure 3

The concept selection criteria are safety, reliability, cost, performance and development risk, with safety given the greatest emphasis.

Concept 4 is the only concept that does not require storage of boiloff, and on this basis has a significant safety advantage.

Refrigerators and high pressure compressor trains have been assumed to have equivalent reliability. Since Concepts 2 and 3 have both refrigeration and compressor equipment, they should be at a disadvantage to Concepts 1 and 4.

Concept 4 has a life cycle cost advantage over the other concepts, although Concept 1 has the lowest IOC cost. If ground rules were to change that currently limit venting of boiloff, Concept 1 could become the clear cost winner.

Concepts 1 and 2 have hydrogen boiloff that must be disposed of and they therefore have lower overall performance than Concepts 3 and 4. Concept 3 uses over twice the electrical energy of Concept 4 and thus Concept 4 is regarded as having the best performance.

CONCEPT SELECTION

	RELATIVE RANKING*			
CRITERIA	CONCEPT 1 PASSIVE	CONCEPT 2 REFRIG.	CONCEPT 3 PARTIAL RELIQ.	CONCEPT 4 TOTAL RELIQ.
Safety	2	2	2	1
Reliability	1	2	2	1
Cost	2	3	4	1
Performance	3	3	2	1
Development Risk	1	3	3	2
TOTALS	9	13	13	6

* 1 is the best rating

Figure 4

The Concept 1 all-passive facility concept includes a single boiloff disposal module affixed at the aft end of one of the tank sets. Four spheres, each five feet in diameter, store gaseous hydrogen boiloff and one 3.5-foot diameter sphere stores the gaseous oxygen boiloff. These vessels are sized to accumulate the 90-day period boiloff plus some contingency for two 100,000 lb capacity tank sets. The other tank set does not have a boiloff disposal module.

The boiloff disposal module is periodically detached and transported away from the Space Station by the OMV and is non-propulsively vented to space.

LONG TERM CRYOGENIC STORAGE FACILITY

All-Passive System Concept with Boiloff Disposal Module

100,000 lb_m Capacity

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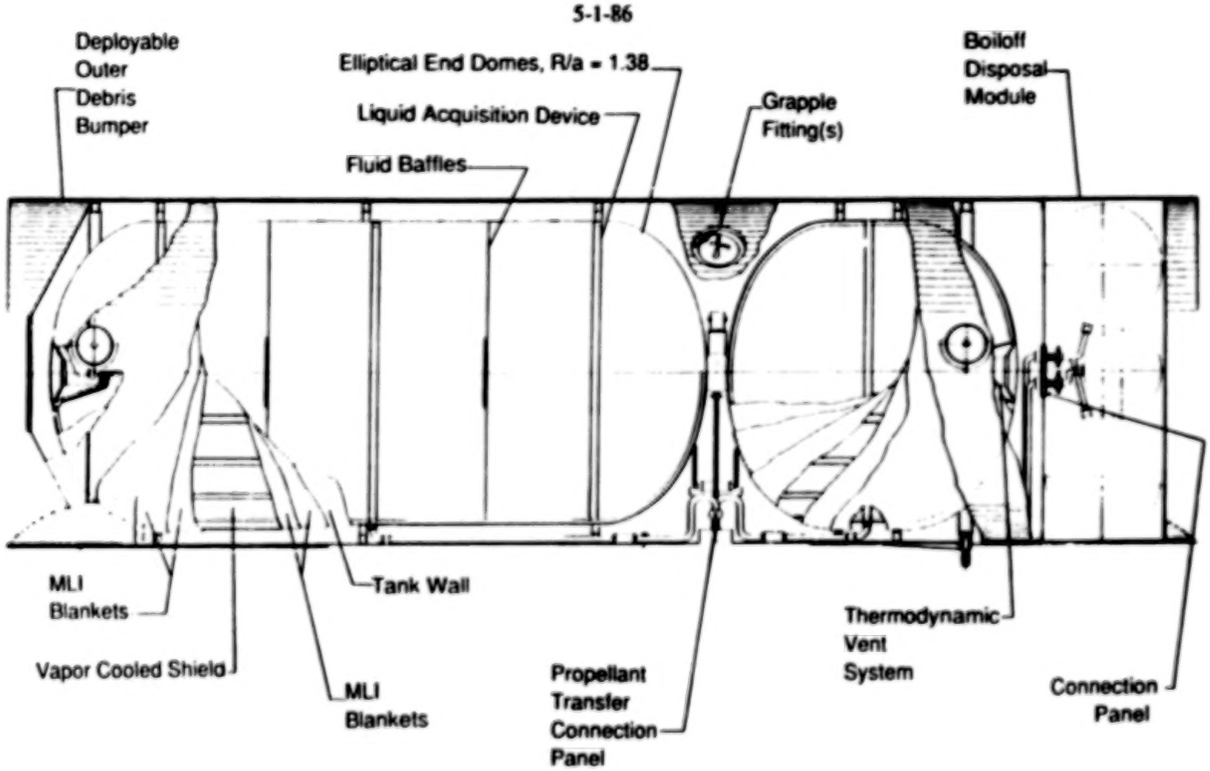

Figure 5

Most of the primary structural elements of the Concept 4 total reliquefaction system are the same as discussed for the all-passive facility. The differences are primarily in the aft bulkhead enclosure where modifications have been made to mount the reliquefaction equipment. Within this compartment are the hydrogen and oxygen pressurant heat exchangers and pumps, the reliquefier and condenser units, and the power conditioning equipment module. All components have been mounted on a graphite epoxy composite isogrid frame to isolate warm side components from cold side cryogenic storage tanks. An access way through the center of the frame is provided since there are doors on the elliptical bulkhead ends of both the hydrogen and oxygen tanks for access to interior on-orbit serviceable and replaceable components, such as the mass gauging instruments, mixers, etc.

A large two-piece door on the aft compartment provides access to the interior equipment modules and serves as the inner component of the two-part micrometeoroid/debris bumper system. Equipment within has been modularized after the design of similar SSP system elements to utilize space servicing tool systems.

LONG TERM CRYOGENIC STORAGE FACILITY

Total Reliquefaction System Concept

100,000 lb_m Capacity

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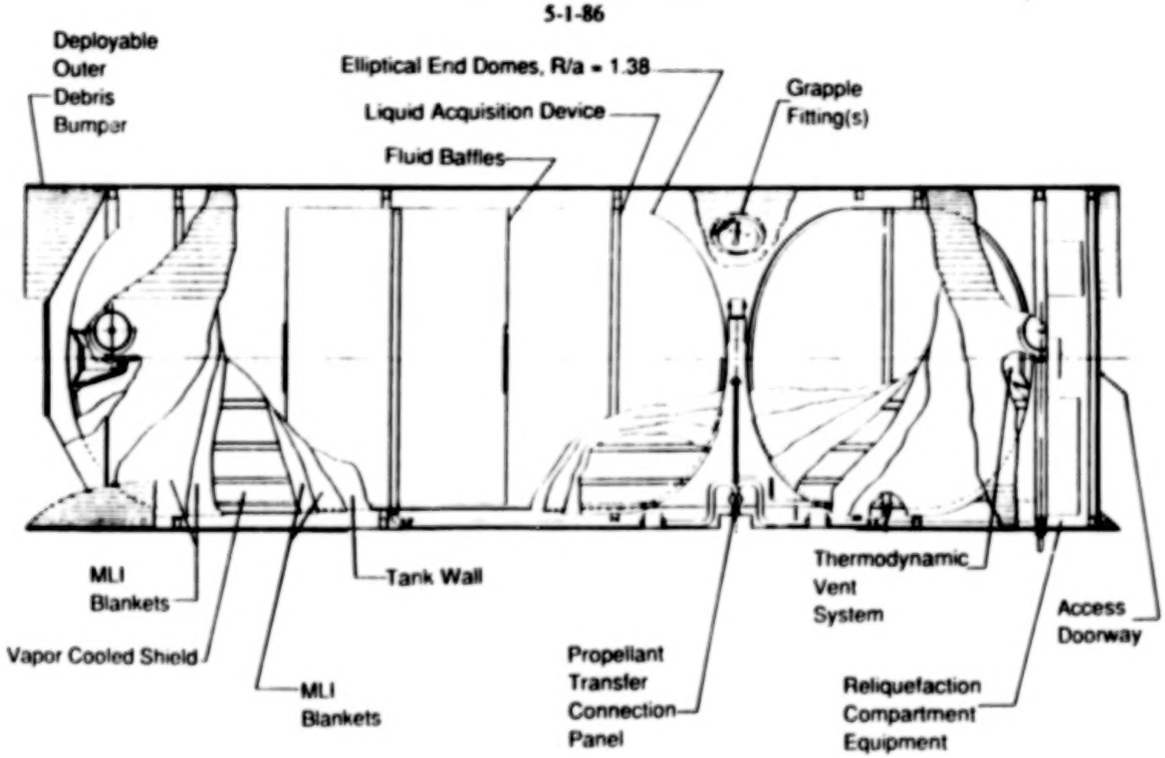

Figure 6

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OF POOR QUALITY

This schematic of the hydrogen fluid subsystem for a single tank set illustrates the features necessary to meet functional requirements and the redundancy necessary to provide single failure operational/dual failure safe capability. Steady-state venting from the system can only occur after at least two failures, provided that redundant power supplies are available. Operationally, the system has been designed to perform long-term fluid storage, tank pressurization for fluid transfer, depot tank or OTV tank prechill, and depot tank or OTV tank no-vent fill.

Two important features of the hydrogen system are the line evacuation subsystem and the prechill bleed subsystem. The line evacuation subsystem reduces the pressure of the fluid in the lines that penetrate the MLI/vapor-cooled shield boundary, minimizing the heat input through these lines. The prechill bleed subsystem is used to remove the fluid from the prechill accumulator in a controlled manner in between OTV servicing operations.

CONCEPT 1: PURE PASSIVE SYSTEM, LH2 FACILITY

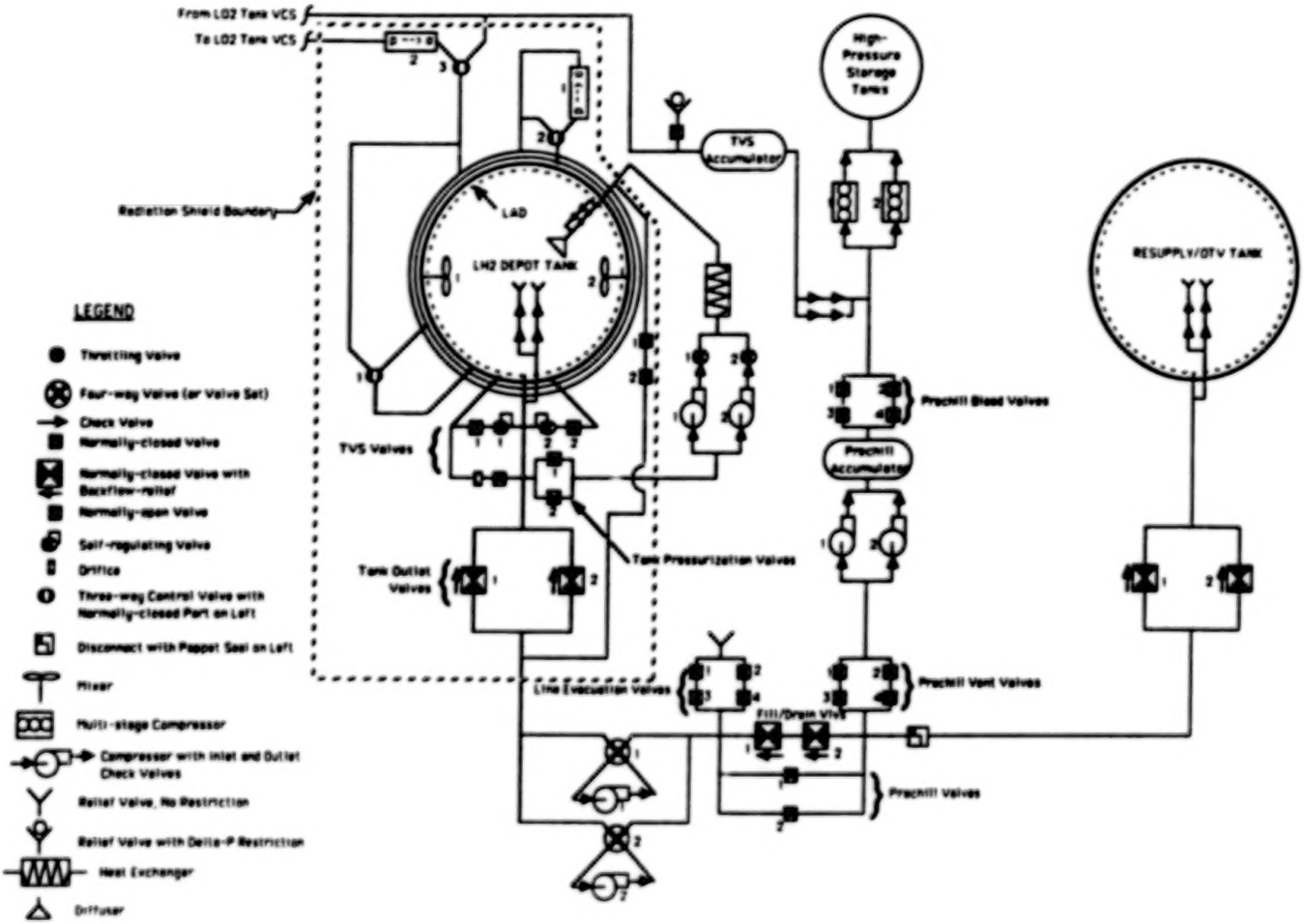

Figure 7

The refrigeration subsystem required for reliquefaction of boiloff uses separate hydrogen and oxygen refrigerators in order to provide the best thermodynamic performance and to permit separate control over the hydrogen and oxygen streams.

The oxygen refrigerators are single-stage devices that provide cooling for both desuperheating and condensing the oxygen boiloff. The hydrogen refrigerators are two-stage devices that provide desuperheating on the first stage and condensing on the second stage. The refrigerators are magnetic suspension, free piston, Stirling machines that are hermetically sealed and use gaseous helium as the refrigerant. Condensate pumps return the condensed liquid to the storage tanks, and circulation pumps provide cooling for both the refrigerators and their control electronics. The refrigerators are heat sinked to the Space Station thermal bus.

CONCEPT 4 REFRIGERATION SYSTEM

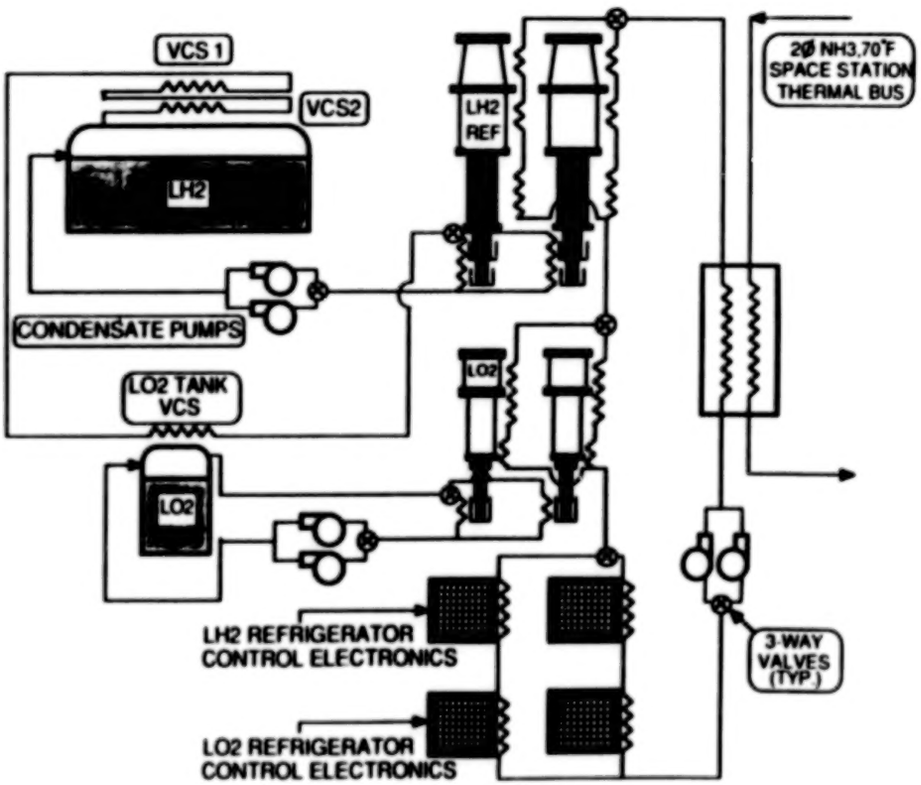

Figure 8

The four storage facility concepts identified during the preliminary concept definition were further defined during the trade studies. The features of the four concepts were reviewed to identify enabling technologies that require research and development prior to making final design option commitments.

Each technology was reviewed to determine its status and identify ongoing efforts to further its development. On the basis of its criticality and status, a justification for further development was prepared along with a brief technical plan, resource estimates and schedule. The estimates were scaled to achieve performance characterization through ground-based components, and include neither on-orbit testing (other than material samples) nor development of flight-qualified components.

Eighteen technology tasks were identified; five tasks were not priced and scheduled because they are to be carried out in connection with the Cryogenic Fluid Management Flight Experiment (CFMFE) program. The costs total $12.18 million and the task durations range from two to six years. The tasks are essentially independent and could be carried out in parallel, if necessary.

TECHNOLOGY DEVELOPMENT CANDIDATES (1)

	Time Req'd Years	Cost $1000
Thick MLI System Development	5	600
VCS Thermal/Structural Integration	3	900
Scaleup and Demonstration of Low Conductance Structural Support	3	400
Para/Ortho Converter Configuration Development(2)	6	280
Solar Thermal Coating Screening and Qualification	4	800
Liquid Acquisition Device Demonstration	CFMFE	
Pressure Control System Demonstration	CFMFE	
Pressurization System Demonstration	CFMFE	
Cryogenic Liquid Transfer Pumps	3	500
Transfer Line/Receiver Tank Chilldown and Fill	CFMFE	
Refrigerator Development(3)	5	5100
Zero-g LH_2/LO_2 Condenser Development(4)	3	450
Zero-g Mass Gauging	CFMFE	
Leak Detection Methods	3	650
Penetration Data Base Development to Support Micrometeoroid/ Debris Shield Design	2	400
Development of Low Conductive Fluid Lines	3	750
Fluid Baffling for Tanks	3	800
Boiloff Storage Compressor Development(5)	3	550
	Total Cost	$12.18M

(1) Exclusive of on-orbit testing
(2) Para/ortho converter not required for Concepts 3 and 4
(3) Refrigerator nor required for Concept 1
(4) Zero-g condenser not required for Concepts 1 and 2
(5) Boiloff storage compressor not required for Concept 4

Figure 9

Storage facility technical risk has been identified by summarizing the critical design and performance issues of individual components. The technical risk is due to uncertainty that components will perform their functions as well as intended. Testing components in representative environments would reduce performance uncertainties and verify design concepts and models. Risks at the component level have been identified as low, medium or high depending on the uncertainty that the component would perform as intended. This risk assessment forms the basis for defining a risk reduction testing program.

STORAGE FACILITY RISK ASSESSMENT

STORAGE FACILITY COMPONENT	CRITICAL DESIGN ISSUES	COMPONENT PERFORMANCE RISK
Tank	• Fluid sloshing and orientation in μ-g env. - Ullage location - Baffle design	Med
	• Tank failure mode	Low
Tank Support Structure	• Dynamic response to launch environment	Med
	• Dynamic interaction with space station	Low
Tank Support Struts	• Support of launch loads	Med
	• Thermal performance	Med
Multiple Layer Insulation (MLI)	• Insulation layup & thermal performance	Med
	• Insulation degradation due to launch	Med
	• Degradation due to atomic oxygen and contamination on orbit	Med
Tank Set Solar Selective Cover	• Coating degradation on orbit	Med
	• Shield thickness and material	Low
Radiator	• Performance	Med
	• Coating degradation on orbit	Med
Micrometeoroid & Debris Shields	• Material and thickness	Med
	• Performance	Med
Vapor-Cooled Shield (VCS)	• Support during launch	Med
	• Thermal performance	Med
Para to Ortho Converter	• Performance	Med
	• Operating life	Low
	• Filtering requirement	Low
Penetrations: Inst. & Plumbing	• Thermal performance	Med
Warm Tank Chilldown	• Procedure - Spray nozzle configuration - Liquid flowrate and duration - Time for temp to reach equilibrium - Number of gas venting steps	Med
	• Zero-g performance	Med
Thermodynamic Vent System (TVS)	• Thermal performance	Med
	• Zero-g performance - Heat transfer from fluid in tank	Med
Stratification / Hot Spot Management	• Mixing needs / Mixing strategy	Med
	• Zero-g performance	Med
Liquid Acquisition Device (LAD)	• Zero-g performance - Residual liquid fraction - Vapor break through vs. flowrate - Maximum flow rate vs. tank liquid % - Pressure drop	Med
	• Long term perf. (corrosion in LOX)	Med

Figure 10

STORAGE FACILITY RISK ASSESSMENT (continued)

STORAGE FACILITY COMPONENT	CRITICAL DESIGN ISSUES DESIGN ISSUES	COMPONENT PERFORMANCE RISK
Pressurization System	• System requirements & performance	Med
	• Zero-g performance	Med
	- Diffuser performance	
	- Optimum flowrate and temperature	
Liquid Pumps	• Operating life	Med
	• Zero-g performance	Low
Refrigerator	• Thermodynamic efficiency and life	High
	• Zero-g performance	Low
Boiloff Condenser	• Thermal performance	Med
	• Zero-g performance	Low
Boiloff Compressor	• Operating life	High
	• Zero-g performance	Low
Low Heat Leak Valves	• Operating life	Med
	• Thermal performance	Med
Disconnects	• Fluid leakage, Pressure drop	Med
	• Force and alignment requirements	Low
	• Thermal performance (heat leak)	Low
Mass Gauging	• Performance	High
	• Zero-g performance	Med
Control System	• System performance, Operating life, & response to component failure	Med
No-Vent Fill	• Procedure	Med
	• Zero-g performance	Med
	- Ullage condensation rates	
	- Fluid mixing requirements	
Transfer Line Chilldown	• Procedure	Low
	• Zero-g performance	Low

Figure 10 (Cont.)

The objective of the test program is to reduce the technical risk associated with fielding an orbital propellant depot. A methodical approach to test program definition was taken by identifying technical risks to the component level, analyzing test article size considerations and defining six test options.

The options were evaluated based on the risk reduction they provide, their compatibility with the overall development schedules for the full scale orbital storage facility, the Space Station and the OTV, and test option cost.

The option recommended involves subscale integrated system testing with hydrogen both on the ground and for a short period on orbit. Extended ground tests would be conducted with active components, liquid acquisition device degradation in liquid oxygen would be investigated, and MLI, solar coatings, and micrometeoroid shield materials would be given extended exposure in low earth orbit.

The recommended test program is estimated to cost $150 million. Contributing to this cost is the extra hardware required for Shuttle qualification of components, and the extensive tasks associated with Shuttle integration of the test hardware.

TEST PROGRAM

OBJECTIVE

- **Reduce The Technical Risk Associated With Fielding An Orbital Propellant Depot**
  - Operating life of active components
  - Zero-g fluid management technology
  - Thermal performance
  - Integrated system performance
  - Degradation of materials on orbit

APPROACH

- Identify techical risks down to component level
- Determine scale of test articles
- Define testing options
- Evaluate options based on resulting risk reduction, schedule compatibility, and cost

CONCLUSIONS / RECOMMENDATIONS

- $150 Million overall cost
- Schedule considerations point towards short term orbital test
- Shuttle qualification requires extra hardware
- Shuttle integration is an extensive task

Figure 11

A contract change order has extended the period of performance through August, 1987, and revised some of the guidelines and assumptions for the study. Additional emphasis was placed on facility interface requirements, cost analyses, and test planning.

CONTRACT CHANGE ORDER

- Extends period of performance through August, 1987
- Revises guidelines and assumptions
  - Dual keel Space Station
  - Orbiting platform
- Requests preliminary interface requirements document
- Requests discounted cost analyses
- Requests preliminary test plan

Figure 12

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SPACE STATION EXPERIMENT DEFINITION: LONG TERM CRYOGENIC FLUID STORAGE

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A preliminary design of an experiment to demonstrate and evaluate long-term cryogenic fluid storage and transfer technologies has been performed. This Long-Term Cryogenic Fluid Storage (LTCFS) experiment is a Technology Development Mission (TDM) experiment proposed by the NASA Lewis Research Center to be deployed on the Initial Operational Capability (IOC) Space Station. Technologies required by future orbital cryogenic systems such as Orbital Transfer Vehicles (OTV's) were defined, and critical technologies requiring demonstration were chosen to be included in the experiment. A three-phase test program was defined to test the following types of technologies:

Phase I	-	Passive Thermal Technologies
Phase II	-	Fluid Transfer Technologies
Phase III	-	Active Refrigeration Technologies

The development status of advanced technologies required for the LTCFS experiment is summarized, including current, past and future programs.

LTCFS STUDY OBJECTIVES

A Technology Development Mission (TDM) experiment was defined by the NASA Lewis Research Center to demonstrate and evaluate long-term cryogenic fluid storage and transfer technologies. The Long-Term Cryogenic Fluid Storage (LTCFS) experiment is to be deployed on the Initial Operational Capability (IOC) Space Station. Cryogenic technologies required by future orbital systems were investigated, and critical technologies required by these systems were chosen for inclusion in the experiment. A conceptual design for this experiment was developed, and Space Station interface and resource requirements were defined and entered into the NASA Space Station data base. An overall program plan for hardware development and on-orbit testing was completed, including Rough-Order-of-Magnitude (ROM) costing. The overall study objectives are as follows:

- DEFINE THE REQUIREMENTS FOR A CRYOGENIC FLUID STORAGE AND TRANSFER EXPERIMENT IN THE FORM OF A SPACE STATION TECHNOLOGY DEVELOPMENT MISSION (TDM) SO THAT SPACE STATION DESIGN DEVELOPMENT EFFORTS WILL MEET FUTURE PROGRAM NEEDS

- IDENTIFY CRITICAL CRYOGENIC FLUID MANAGEMENT TECHNOLOGIES THAT REQUIRE EVALUATION WITH NASA LERC'S PROPOSED TDM

- DEVELOP A CONCEPTUAL EXPERIMENT DESIGN FOR THE TDM WHICH ACCOMMODATES THE TECHNOLOGY DEMONSTRATION OBJECTIVES IN A TIMELY MANNER

- DEFINE AND DOCUMENT THE SPACE STATION INTERFACE AND RESOURCE REQUIREMENTS NECESSARY TO SUPPORT THE TDM

- PREPARE A PLAN FOR THE OVERALL PROGRAM FROM HARDWARE DEVELOPMENT THROUGH EXPERIMENT COMPLETION

LTCFS EXPERIMENT DESCRIPTION

The conceptual design of the LTCFS experiment is modular, allowing testing to be performed in the three phases described below. The modularity of the experiment allows for maximum flexibility in experiment development and scheduling. Over the four-year experiment period, modules will be added to the initial configuration to perform additional testing. This modularity also allows a wide range of potential future uses of the experiment after experiment termination.

- THE LONG TERM CRYOGENIC FLUID STORAGE EXPERIMENT IS MODULAR, CONSISTING OF THREE PHASES TO TEST THE FOLLOWING TECHNOLOGIES:

  PHASE I - PASSIVE THERMAL TECHNOLOGIES
  PHASE II - FLUID TRANSFER TECHNOLOGIES
  PHASE III - ACTIVE REFRIGERATION TECHNOLOGIES

- THE EXPERIMENT WILL BE DEPLOYED ON THE IOC SPACE STATION FOR A PERIOD OF FOUR YEARS

- MODULES WILL BE ADDED TO THE PHASE I HARDWARE TO RECONFIGURE THE EXPERIMENT FOR PHASE II AND III TESTING

- THE LTCFS EXPERIMENT COULD BE UTILIZED FOR FURTHER ORBITAL TESTING OR FOR SPACE STATION CRYOGENIC STORAGE AFTER TERMINATION OF PHASE I-III TESTING

PHASE I DESCRIPTION

Phase I of the experiment, depicted in Figure 1, will test passive thermal control technologies that are utilized to achieve long term storage of cryogens. The Phase I hardware consists of a 6.5 m^3 (228 ft^3) liquid hydrogen dewar supported in a structure that will be mounted to the Space Station truss structure. The experiment dewar will utilize numerous advanced technologies, such as dual stage supports and a thick multi-layer insulation blanket that allows long term storage of the cryogen. The tank will be instrumented to allow on-orbit thermal performance of the tank to be evaluated. Phase I testing will last for a period of two years.

PHASE I - EXPERIMENT CONFIGURATION

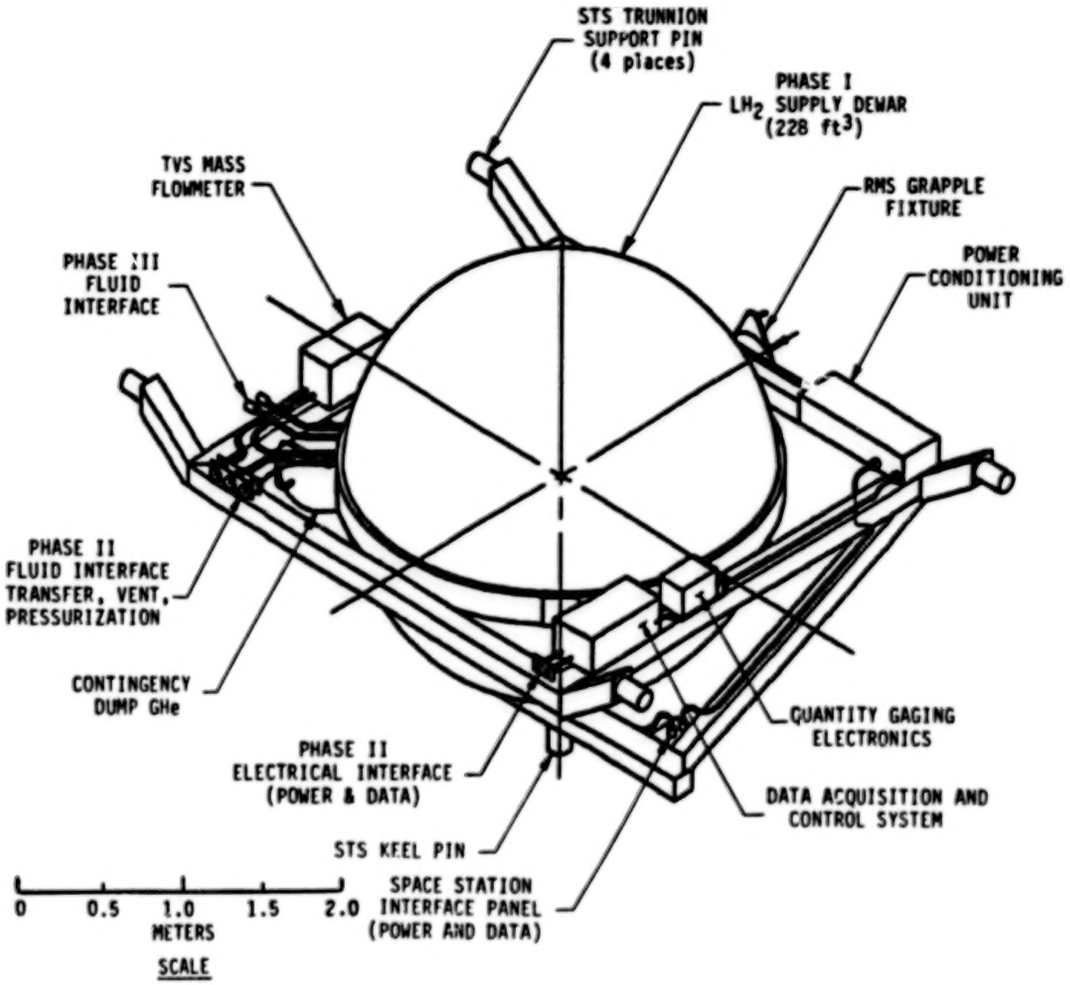
STS TRUNNION SUPPORT PIN (4 places)
PHASE I LH_2 SUPPLY DEWAR (228 ft^3)
TVS MASS FLOWMETER
RMS GRAPPLE FIXTURE
PHASE II FLUID INTERFACE
POWER CONDITIONING UNIT
PHASE II FLUID INTERFACE TRANSFER, VENT, PRESSURIZATION
CONTINGENCY DUMP GHe
QUANTITY GAGING ELECTRONICS
PHASE II ELECTRICAL INTERFACE (POWER & DATA)
DATA ACQUISITION AND CONTROL SYSTEM
STS KEEL PIN
SPACE STATION INTERFACE PANEL (POWER AND DATA)
0 0.5 1.0 1.5 2.0
METERS
SCALE

Figure 1

PHASE I - TECHNOLOGY DEMONSTRATIONS AND DEVELOPMENT STATUS

The technologies listed below are those advanced technologies required in Phase I that are not yet fully developed for flight. The development status of these technologies is outlined, including any current or future ground and flight development.

TECHNOLOGY	DEVELOPMENT STATUS
DUAL STAGE SUPPORT	LOCKHEED - PODS DESIGN DEVELOPMENT AND HARDWARE TESTING BALL - RITS - DESIGN DEVELOPMENT ONLY
PARA-ORTHO H_2 CONVERSION	GROUND DEMONSTRATIONS ONLY (LOCKHEED, BEECH AIRCRAFT)
THICK MLI	CFMFE, AIR FORCE RPL
THERMODYNAMIC VENT SYSTEM	CFMFE, SHUTTLE PRSA TANKS (VAPOR COOLED SHIELDS ONLY)
STRATIFICATION CONTROL	CFMFE, CENTAUR
THERMAL CONTROL COATINGS/ DEGRADATION	LONG DURATION EXPOSURE FACILITY (LDEF) PLUS NUMEROUS SATELLITES AND MANNED SPACEFLIGHT APPLICATIONS

TECHNOLOGY ISSUES	
LOW-G LONG-TERM STRATIFICATION	NO CURRENT PROGRAMS
MICRO-METEROID PROTECTION	GROUND TESTING HAS BEEN PERFORMED (BOEING)

PHASE II DESCRIPTION

Phase II of the LTCFS experiment, depicted in Figure 2, will test fluid transfer technologies. The experiment is reconfigured by adding a module containing a receiver tank and pressurization system to the Phase I hardware. The receiver tank is a 1.3 m^3 (45 ft^3) soft outer shell tank containing spray nozzles for tank cooldown and a screen acquisition device to allow backflow into the Phase I supply dewar. The pressurization system utilizes a metal hydride compressor that collects boiloff from the supply and receiver tanks, and stores it in a 0.6 m^3 (21 ft^3), 3.4 mPa (500 psia) pressurant accumulator. When the accumulator is fully charged, a transfer operation from the supply tank to the receiver tank is performed. The thermal performance of the receiver tank will also be evaluated during Phase II. Phase II testing will be performed for a period of one year.

PHASE II EXPERIMENT CONFIGURATION

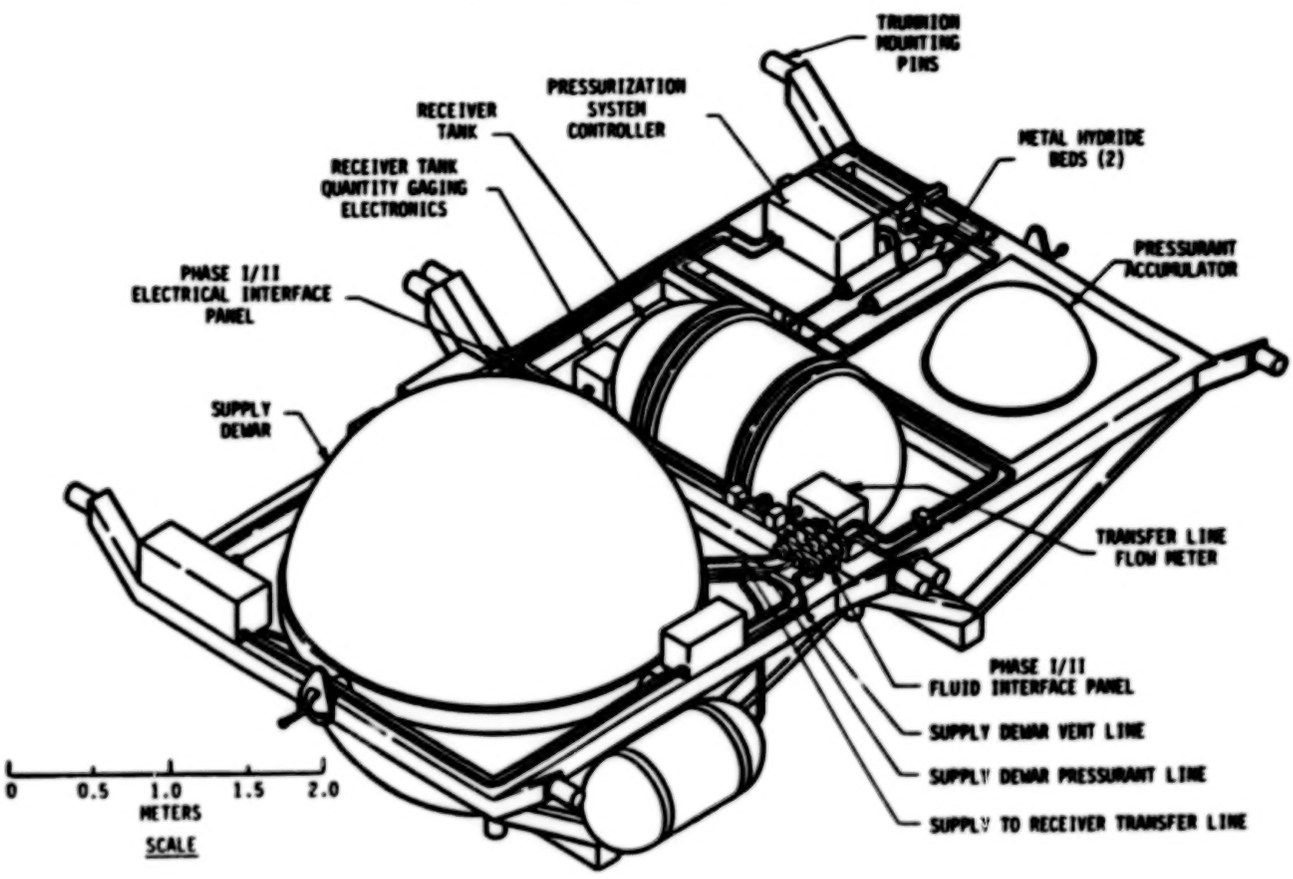

Figure 2

PHASE II - TECHNOLOGY DEMONSTRATIONS AND DEVELOPMENT STATUS

The technologies listed below are those advanced technologies required in Phase II that are not yet fully developed for flight. The development status of these technologies is outlined, including any current or future ground and flight development.

TECHNOLOGY DEMONSTRATED	DEVELOPMENT STATUS/PROGRAMS
CAPILLARY ACQUISITION	CFMFE
QUANTITY GAGING	CFMFE, NASA-JSC RF GAGING (NO FLIGHT TESTING)
MASS FLOW METERS	CFMFE
LOW HEAT LEAK VALVES	GROUND DEVELOPMENT
LOW HEAT LEAK TRANSFER LINES	GROUND DEVELOPMENT
CRYOGENIC DISCONNECTS	GROUND DEVELOPMENT, ORBITAL REFUELING DISCONNECT FOR EARTH-STORABLE FLUIDS UNDER DEVELOPMENT (JSC)
BOILOFF COLLECTION FOR EXTERNAL PRESSURIZATION	CONCEPTUAL DESIGN ONLY
METAL HYDRIDE COMPRESSOR	GROUND DEVELOPMENT
SOFT OUTER SHELL TANK	SEVERAL GROUND TESTS, CFMFE
SOFT OUTER SHELL PERFORMANCE DEGRADATION	NO CURRENT PROGRAMS

PHASE III DESCRIPTION

Phase III of the experiment, depicted in Figure 3, will test active refrigeration technologies. The experiment is reconfigured by interfacing an active refrigeration unit with the Phase I supply dewar. This refrigeration unit will circulate coolant through a parallel path within the supply dewar's thermodynamic vent system to provide refrigeration to the tank and reduce or eliminate tank boiloff. The Phase III module will utilize a high reliability, long-lifetime cryogenic refrigerator.

PHASE III EXPERIMENT CONFIGURATION

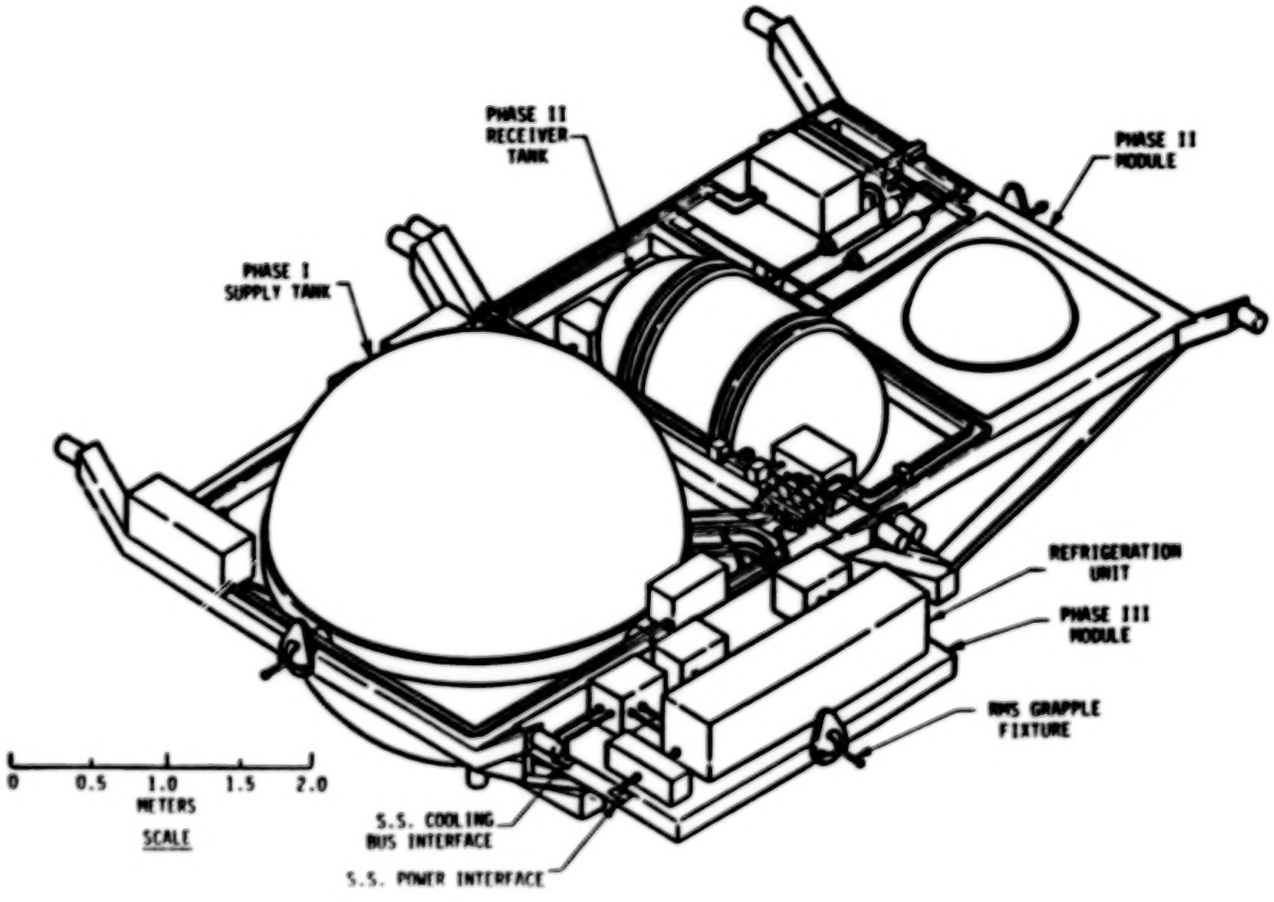

Figure 3

PHASE III – TECHNOLOGY DEMONSTRATIONS AND DEVELOPMENT STATUS

The technologies listed below are those advanced technologies required in Phase III that are not yet fully developed for flight. The development status of these technologies is outlined, including any current or future ground and flight development.

TECHNOLOGY DEMONSTRATED	DEVELOPMENT STATUS/PROGRAMS
LONG LIFETIME REFRIGERATOR	NUMEROUS GROUND DEVELOPMENT PROGRAMS: NASA - PHILLIPS MAGNETIC STIRLING - OXFORD SPLIT STIRLING CYCLE AIR FORCE - VUILLEUMIER - SORPTION REFRIGERATOR - MAGNETIC REFRIGERATOR - BRAYTON CYCLE
CRYOGENIC COOLANT CIRCULATOR	NO CURRENT DEVELOPMENT
CRYOGENIC HEAT EXCHANGER	UNITS ARE BEING DEVELOPED FOR BRAYTON CYCLE REFRIGERATOR

TECHNOLOGY HARDWARE MATRIX

The table shown below lists the advanced technologies required by Orbital Transfer Vehicle (OTV) cryogenic systems. All technologies listed require some amount of future development or flight testing prior to utilization. These requirements are outlined for the Resupply Tanker that delivers propellant to low-earth orbit, the Space Station Tank Farm that stores the propellant prior to OTV refueling, and the OTV itself. Also listed under the heading of Future Experiments are the technologies that are to be developed and/or demonstrated by the Cryogenic Fluid Management Flight Experiment (CFMFE) and the LTCFS experiment. This summary was a result of the technology investigation performed during the design study that chose critical technologies to be included in the LTCFS experiment.

	FUTURE REQUIREMENTS			FUTURE EXPERIMENTS	
	RESUPPLY TANKER	OTV	SPACE STATION TANK FARM	CFMFE	LTCFS
PASSIVE THERMAL TECHNOLOGIES					
Dual Stage Support			X		X
Para-Ortho Conversion			X		X
Thick MLI		X	X	X	X
TVS	X	X	X	X	X
Thermal Coatings		X	X		X
Soft Outer Shell		X	X	X	X
Hard Outer Shell	X			X	X
FLUID TRANSFER					
Capillary Acquisition	X	X	X	X	X
Low-G Quantity Gaging	X		X	X	X
Mass Flow Meters	X		X	X	X
Low Heat Leak Valves	X		X		X
Low Heat Leak Transfer Lines	X		X		X
Cryogenic Disconnects	X	X	X		X
External Pressurization	X	X	X		X
HPG Pressurization				X	X
Metal Hydride Compressor					X
ACTIVE REFRIGERATOR					
Long Lifetime Refrigerator			X		X
Reliquefaction			X		X
Cryogenic Heat Exchanger			X		X
Refrigerator to S.S. Thermal Bus HEX			X		X

TECHNOLOGY ISSUE MATRIX

The table shown below is identical to the previous table, but outlines technology issues involved with future orbital systems. These issues include orbital environment phenomena, fluid management, and logistics. As before, issues that will be addressed by the CFMFE and LTCFS experiment are also listed.

	FUTURE REQUIREMENTS			FUTURE EXPERIMENTS	
	RESUPPLY TANKER	OTV	SPACE STATION TANK FARM	CFMFE	LTCFS
INVESTIGATED PHENOMENA					
Long-Term Stratification Effects			X		X
Soft OS Performance Degradation		X	X		X
Thermal Coating Degradation		X	X		X
Micro-Meteroid Protection		X	X		X
FLUID MANAGEMENT					
LAD Refill		X	X	X	X
Transfer Line Cooldown	X	X	X	X	X
ET Scavenging	X				POSSIBLE
Receiver Tank Cooldown	X	X	X	X	X
Receiver No-Vent Fill		X	X	X	X
Refill of Partially Full Tank			X	X	X
Propellant Settling		X		X	
Boiloff Collection			X		X
Slosh Suppression	X	X	X		
ON-ORBIT LOGISTICS					
System Safing	X	X	X	X	X
Space Station Interfacing	X	X	X		X
Space Station Operations	X	X	X		X
On-Orbit Leak Detection	X	X	X		POSSIBLE

SUMMARY

The technologies listed below are required by the LTCFS experiment but have no current flight development scheduled. Also shown are issues and technologies for which no development testing is currently defined.

- THE FOLLOWING TECHNOLOGIES REQUIRED FOR THE LTCFS EXPERIMENT CURRENTLY HAVE NO FLIGHT DEVELOPMENT SCHEDULED:

  DUAL STAGE SUPPORTS
  PARA-ORTHO H_2 CONVERSION
  CRYOGENIC TANK MICRO-METEROID PROTECTION
  LOW HEAT LEAK VALVES
  LOW HEAT LEAK TRANSFER LINES
  CRYOGENIC DISCONNECTS
  CRYOGENIC HEAT EXCHANGER
  METAL HYDRIDE COMPRESSOR
  LONG LIFETIME REFRIGERATOR

- THE FOLLOWING TECHNOLOGIES HAVE NO CURRENT OR SIGNIFICANT PAST DEVELOPMENT PROGRAMS:

  LOW-G LONG TERM STRATIFICATION
  SOFT OUTER SHELL PERFORMANCE DEGRADATION
  BOILOFF COLLECTION FOR EXTERNAL PRESSURIZATION
  CRYOGENIC COOLANT CIRCULATOR

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HELIUM TECHNOLOGY ISSUES

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Moffett Field, California

A number of future space missions require liquid helium for cooling scientific payloads. These missions will require the long term storage and resupply of liquid helium at temperatures of 1.4 - 2.1 kelvin. In addition, some of the proposed instruments will require refrigeration to temperatures as low as 50 mK. A variety of liquid helium based refrigerator systems could provide this subkelvin cooling. The status of helium storage and refrigeration technologies and of several alternative technologies is presented here along with areas where further research and development are needed. (Helium resupply technologies are the topic of another presentation at this symposium.) The technologies covered include passive and dynamic liquid helium storage, alternatives to liquid helium storage, ^3He refrigerators, $^3He/^4He$ dilution refrigerators, and alternative sub-kelvin coolers.

BACKGROUND

A number of planned missions will require temperatures below 2 kelvin. These low temperatures are needed for cooling infrared detectors for long wavelength background limited astrophysical observations and for cooling novel x-ray and gamma-ray astrophysics instruments. The low temperatures are also required for a number of high sensitivity physics experiments and for the helium resupply kit. A partial list of these experiments is given in the chart below.

MISSIONS REQUIRING LIQUID HELIUM

Mission	Liquid Helium Storage	Sub-kelvin Cooling
ASTRONOMY		
SIRTF	x	x
AXAF	x	x
LDR	x	x
Astromag	x	
Small IR telescopes	x	?
PHYSICS		
GP-B	x	
Lambda point	x	
Tricritical point	x	x
OTHER		
SHOOT	x	
Helium resupply kit	x	

LIQUID HELIUM STORAGE

Superfluid helium ($T<2.17K$, $P<5kPa$) is used on space missions because of its ease of containment and other physical properties. Such stored helium systems can provide cooling down to about 1-1.2 K. Future missions will require longer storage times, higher heat loads, and probably have more stringent ground operational requirements than in the past. These requirements can be summarized as:

- 2+ Year on orbit operational lifetime (except for shuttle based missions)
- Heat loads up to 1 watt
- 72+ Hours of ground hold between last service and launch

Technology issues relating to these requirements can be divided into several categories. These are passive storage techniques, dynamic storage techniques, extended ground hold techniques, and alternative approaches.

PASSIVE STORAGE TECHNOLOGY

Technology	Status	Issues
Supports	PODS-III demonstrated on ground up to x10 lower orbital conductivity PODS-IV improved side load capability	Interaction between low orbital resonant frequency and bulk fluid motion mission dependent trade-off between PODS and straps
Insulation	Double aluminized polymers with spacers in vacuum is SOA	Optimum packing for low boundary temperatures is unknown; performance is highly dependent on lay-up technique
Bulk fluid motions	Preliminary experiments (SFHE) were inconclusive	Unknown location of fluid, slosh modes, slosh damping

LONG-LIFETIME HELIUM DEWAR

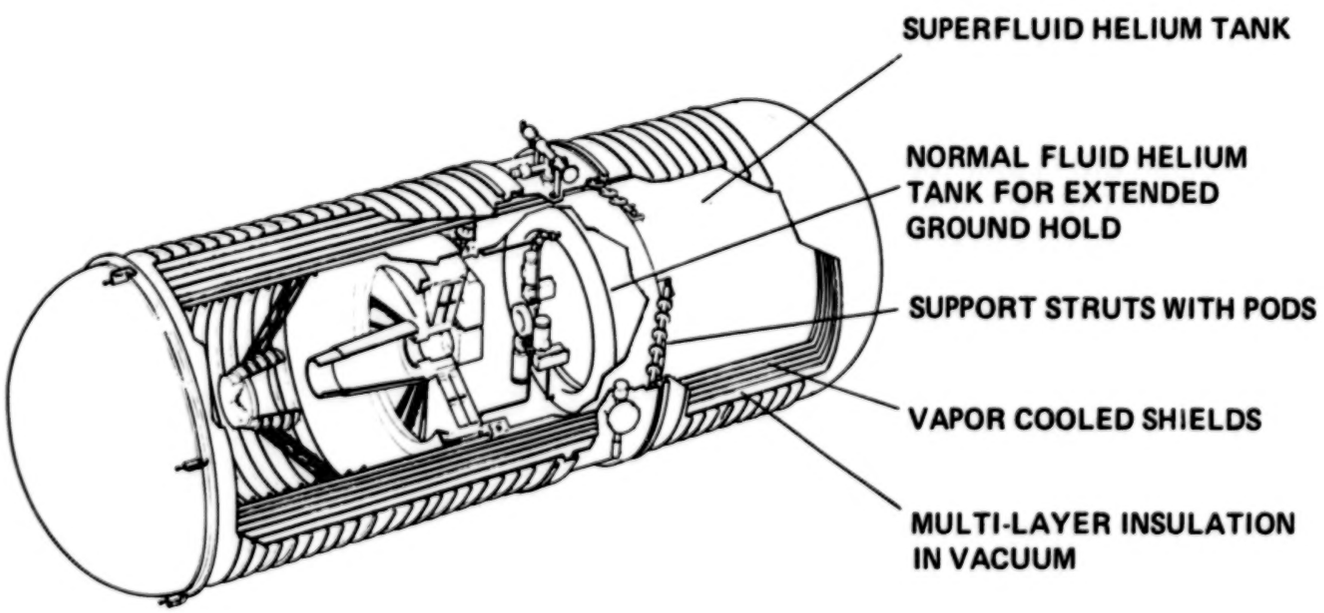

SUPERFLUID HELIUM TANK
NORMAL FLUID HELIUM TANK FOR EXTENDED GROUND HOLD
SUPPORT STRUTS WITH PODS
VAPOR COOLED SHIELDS
MULTI-LAYER INSULATION IN VACUUM

Figure 1

The Passive Orbital Disconnect Strut (PODS)[1] is the only significant advance in dewar support structures. The PODS is a variable strength, variable thermal conductance tank support. It has two configurations. A high strength configuration for launch loads and a low thermal conductance configuration for orbital and ground operations. These supports change passively from the orbital configuration to the launch configuration by the application of the launch load. Upon the removal of this load, the configuration changes reversibly back to the orbital configuration. Extensive ground testing of the thermal and mechanical properties of the PODS have been carried out. These tests include measurements of the thermal conductivity, of thermal contraction effects, of loads in excess of Shuttle loads, of fatique strength, and of the effect of side loads. In all cases they have met or exceeded expectations. They are ready for use in space missions.

The only remaining issues are the mission dependant trade-off studies between PODS and conventional straps and the effect of the interaction between the lower orbital resonant frequency of PODS and the bulk motions (sloshing) of the fluid. The latter is only expected to be significant in missions that require high accuracy pointing; such as SIRTF and LDR. Unfortunately, it is difficult to simulate low-g sloshing motions on the ground, so a study of this interaction needs to be done in space.

DEWAR SUPPORT WITH PASSIVE ORBITAL DISCONNECT (PODS)

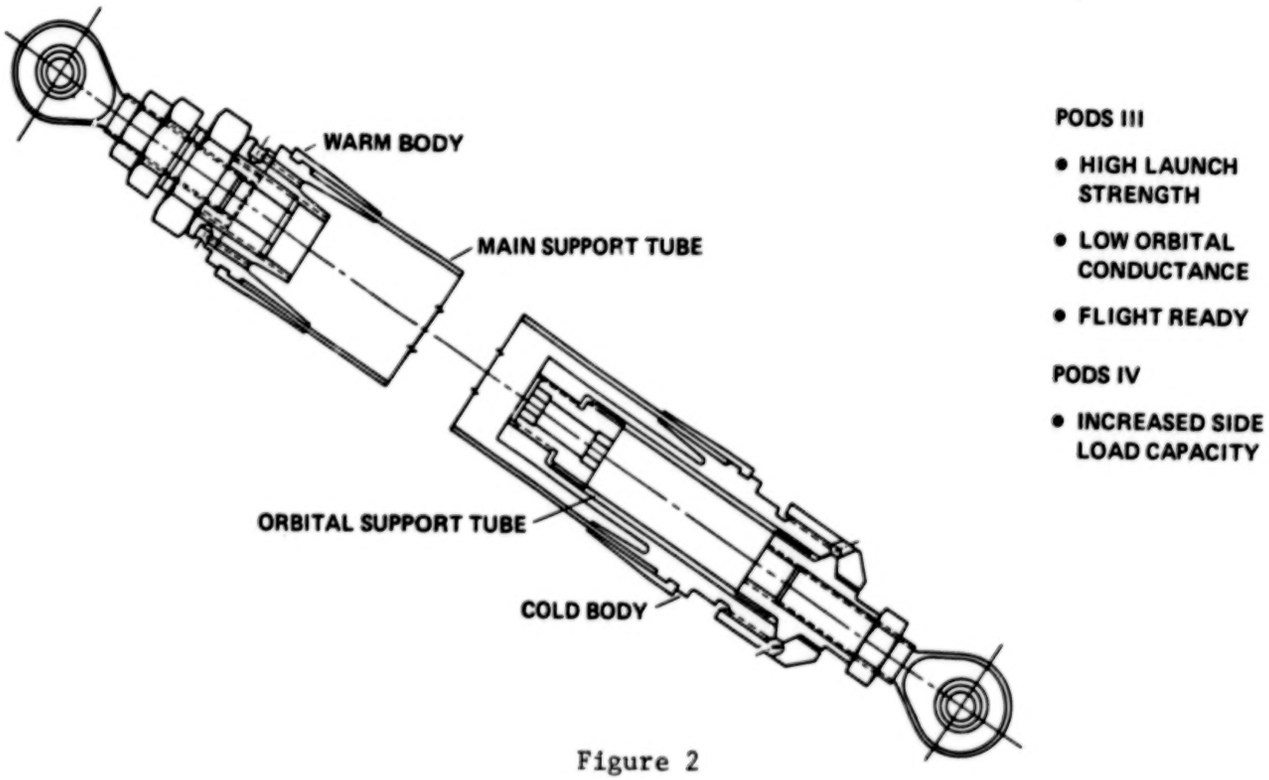
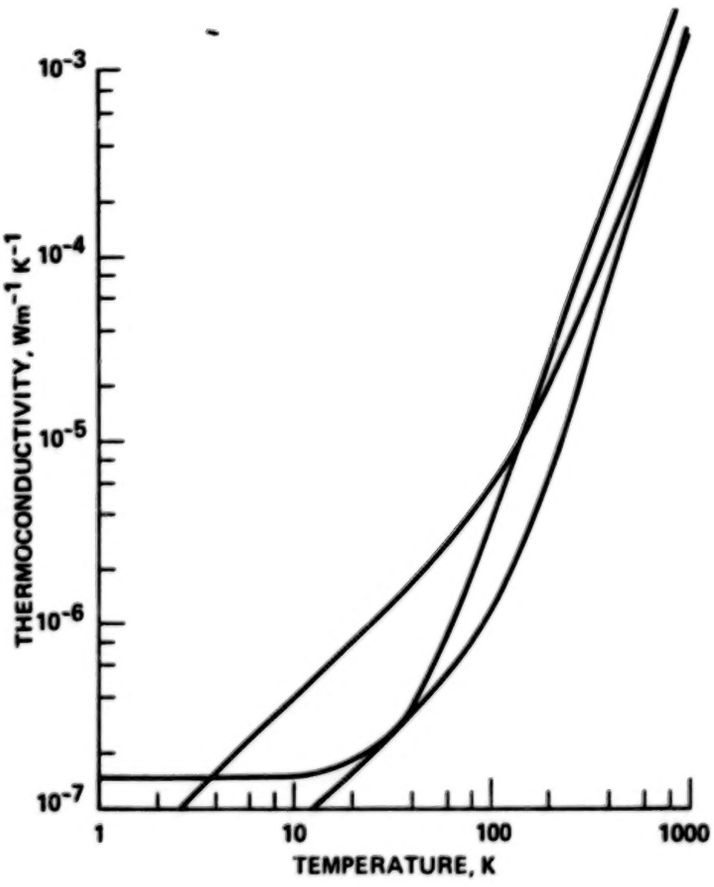


Figure 2

The state of the art insulation systems is multi-layer blankets of double aluminized mylar separated by spacers (such as silk net). These blankets operate best in vacuum. Unfortunately, the performance of the insulation is very dependent on the care taken in preparing and applying the blankets. Another factor in their performance is the packing density of the layers. The effect of the packing density is reasonably well known at high temperatures. At issue is the optimum packing in the 2-20 K range where measurements are very difficult to make.

MULTI-LAYER INSULATION



- HIGH-TEMPERATURE PERFORMANCE KNOWN
- PERFORMANCE LAY-UP DEPENDENT
- LOW TEMPERATURE BEHAVIOR UNKNOWN

Figure 3

The final technology area in passive systems relates to the bulk behavior of the stored fluid. There are three issues here. The first is the distribution of the bulk liquid within the tank. Theory predicts that, in space, in a partially full helium dewar, the liquid will completely cover the wall while the vapor will reside in a single bubble. Sounding rocket experiments by the Japanese tend to confirm this. A more extensive experiment (SFHE) produced inconclusive results[2]. The knowledge of where the helium resides is critical to missions, such as GP-B, that are extremely sensitive to the location and stability of the center of mass of the liquid. The second issue is to understand the slosh modes and their damping. The viscosity of superfluid helium has an unusual behavior. At low velocities it exhibits no viscosity and thus sloshing can be expected to persist for longer times than it would in ordinary fluids. (In low-g, sloshing of ordinary fluids damps out rapidly.) Previous attempts to measure these effects were limited to the last 10% of fill on IRAS. Thus, they did not measure the region where slosh is expected to be the greatest (50% full). Large slosh effects would affect the pointing stability of helium cooled telescopes such as SIRTF, AXAF, GP-B and LDR. A knowledge of the amplitude and damping of the slosh modes will be needed to design baffles to suppress the slosh and to design the fine pointing control system to react against the slosh in these telescopes. The final issued is an extension of the first two. It is to develop fluid management devices to control the location and slosh of the fluid. A variety of missions will require this additional liquid control. These include GP-B which has a particularly stringent requirement on the control of the liquid's center of mass. Another mission is the liquid helium resupply kit where a liquid management device is required to keep the liquid at the pump inlet during adverse accelerations[3]. While a variety of management devices have been used in space to control different liquids, they have not been used to control saturated liquids (as will be required for liquid helium systems). Also, they have not been used with superfluid helium which has a thick creeping film, no viscosity (at low velocities), and a low surface tension (an order of magnitude lower than previously used fluids).

An alternative to the purely passive storage, is the hybrid technique of dynamic storage. In dynamic storage systems, some of the parasitic heat loads on the stored cryogen are intercepted by refrigerated shields. This approach has several advantages: 1) the refrigerators need not run at the ultimate system operating temperature; as cooling just the higher temperature shields can significantly reduce the quantity of liquid needed; and 2) the refrigerators need not

survive the whole mission; as the stored liquid will remain for a while after the refrigerator has failed. This comes with the disadvantages of increased complexity. Whether or not the resulting system is lighter and smaller will be mission dependent. In general, there are two issues with dynamic systems. The first is the lifetime of the coolers. The more important issue is how to optimize a dynamic storage system. Such an optimization must consider such factor as thermodynamics, mass, volume, and cost among other considerations[4].

DYNAMIC STORAGE TECHNOLOGY

Technology	Status	Issues
Closed-cycle coolers		Lifetimes, system system optimization
- Magnetic stirling	Single-stage demonstrated	
- adsorption/ JTX	8 K unit under development	
- pulse tube	single-stage brassboard	

DYNAMIC STORAGE

EXTENDED CRYOGEN LIFETIME BY SUB-COOLING SHIELDS

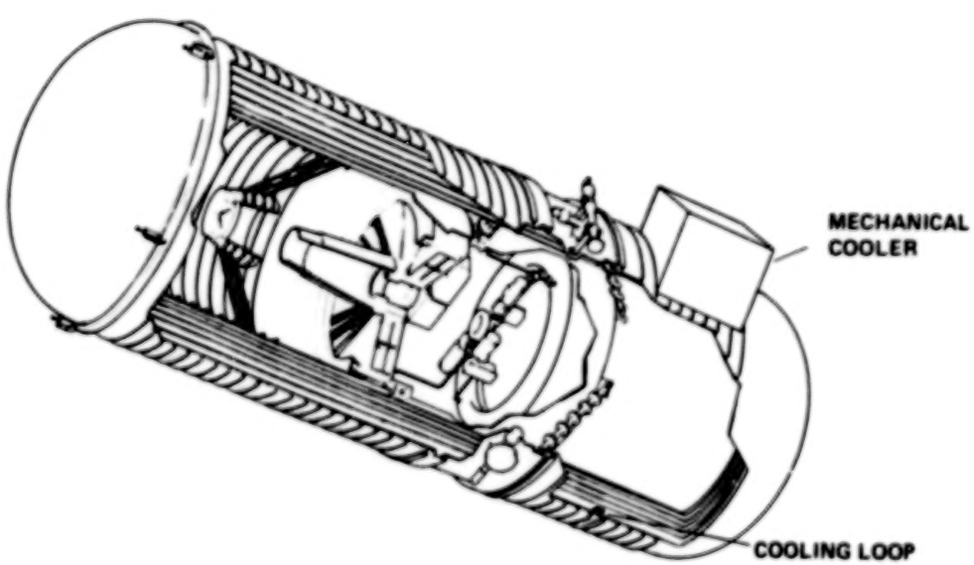


Figure 4

In recent years three novel refrigerators, that could be used in dynamic systems, have been under development at NASA. These are the Magnetic Stirling (GSFC), the Adsorption Joule-Thomson (JPL), and the Pulse Tube (ARC). The current status of these refrigerators will be reported in more detail at this years Cryocooler Conference (Easton MD, Sept. 25-26, 1986). Briefly, the magnetic stirling eliminates wear by using magnetic bearings. This is a complex system, but a considerable number of operating hours has been achieved on a single stage cooler. Multi-stage units should be able to reach temperatures down to approximately 10 K. A multi-stage adsorption cooler is under development. The current goal is a 8 K, although lower temperatures are possible. One advantage of this type of cooler is that the only moving part is a room temperature compressor. This greatly simplified the seals and bearings problem. However, the compressor must be a multi-stage device since a number of different gasses must be compressed with a high pressure ratio. Another refrigerator that has a room temperature compressor as its only moving part is the pulse tube refrigerator. Here, the compressor is a single stage unit with a low pressure ratio and a large displacement. A single stage brass-board has been built and has a performance similar to single stage stirling coolers. A multi-stage unit should be capable of temperatures below 20 K. Since the pulse tube is the least well known of these cycles, it is illustrated here.

PULSE TUBE REFRIGERATION

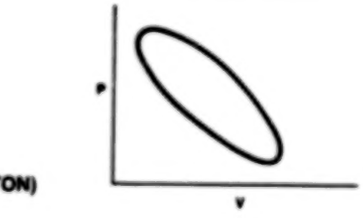
INHERENTLY IRREVERSIBLE

ONE MOVING PART (ROOM TEMPERATURE PISTON)
NO COLD MOVING PARTS

EFFICIENCY APPROACHES THAT OF A STIRLING CYCLE

300-60 KELVIN IN SINGLE STAGE
CAN BE STAGED FOR LOWER TEMPERATURES

MISSIONS REQUIRING LONG LIFETIME MECHANICAL COOLER



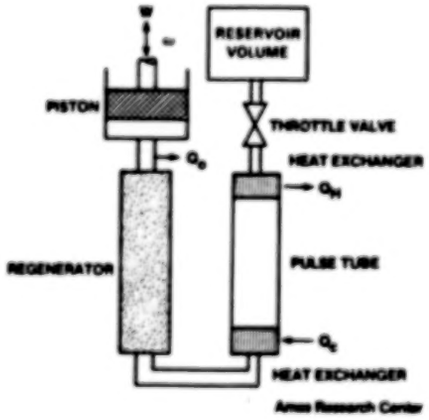


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Figure 5

The limited ability to service spacecraft prior to launch has caused many difficulties with liquid helium systems. Missions such as GP-B and SHOOT are considering new approaches. GP-B is including a second helium tank. The tank holds only enough helium at atmospheric pressure (4.2K) to last during ground operations[5]. During which time it reduces the parasitic load on the main tank by subcooling the inner most shield.

SHOOT is taking another approach[6]. This is to launch with atmospheric helium and to pump down to the operating pressure on the way to orbit. This greatly simplifies ground operations at the expense of loosing 30-50% of the helium volume during the conversion process. At issue is how to contain the liquid during pump down in zero-g until the superfluid transition is reached (where upon existing techniques can be used to contain the helium). The technology to do this containment is only in the early stages of laboratory testing.

EXTENDED GROUND HOLD TECHNOLOGY

Technology	Status	Issues
Sacrificial tank	Concept only	Trade extra hold time for extra mass/ complexity
In-orbit conversion	Preliminary ground testing of one concept	Not yet demonstrated in flight

The alternative to storing liquid helium for instrument cooling is to replace it with a closed cycle refrigerator. Such a refrigerator would have to provide cooling to well below 2 K. Unfortunately, there are few refrigerators capable of doing this on the ground let alone in space. (Perhaps, the effort to develop the Superconducting Supercollider will improve things on earth.) For space applications, a suitable cooler could be made by adding an appropriate Joule-Thomson stage to a multi-stage version of any of the refrigerators discussed earlier. At present there is no effort to do this.

ALTERNATE TECHNOLOGIES

Technology	Status	Issues
Closed-cycle coolers	No suitable coolers	

SUB-KELVIN COOLERS

The general requirements for subkelvin coolers can be summarized as

- Operating temperatures:
  - various, over range 0.05-0.9 K
  - single cooler need not span entire range
- Heat load
  - 0 (absorb parasitic load only)
- Duty cycle
  - 85% to continuous
  - minimum time between recycling mission dependent
    - 20 min. for SIRTF (10-20 hr. preferred)

These requirements do not include single shot coolers that could operate only once per mission. Such coolers could be used on short missions or on missions where resupply were possible.

^{3}He refrigerators work by evaporative cooling of liquid ^{3}He. A problem of using this type of refrigerator in space is keeping the liquid near the detector while maintaining good thermal contact. A potential refrigerator has been tested on the ground in an inverted geometry where a high conductivity porous material was used to both confine the liquid, and to conduct the heat from the bolometer to the liquid[7]. The effect of the larger pores on the heat transfer in low-g in the presence of both saturated liquid and vapor within the pores in unknown.

SUB-KELVIN COOLERS

Technology	Status	Issues
^{3}He refrigerators	Demonstrated on ground	Fluid retention with heat transfer in space
Dilution refrigerator	Conceptual only	Phase separation

SUB-KELVIN COOLERS FOR LONG WAVELENGTH ASTRONOMY

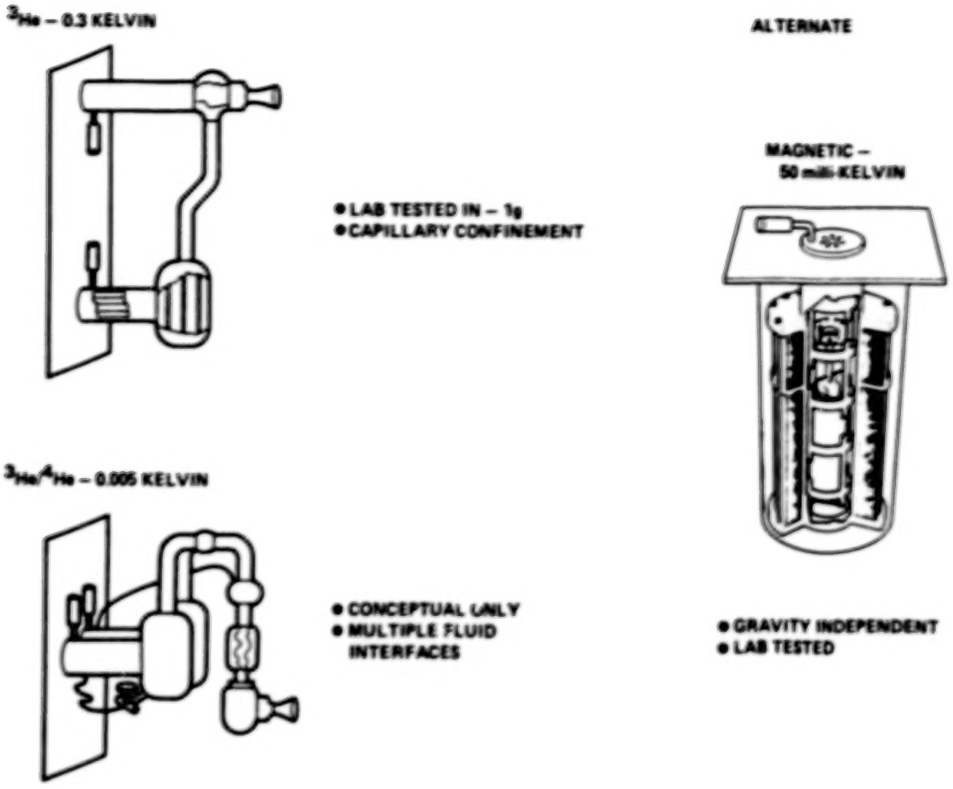

Figure 6

The preferred method to reach temperatures in the 0.005-0.5 K range in the laboratory is with dilution refrigerators. They are preferred because they can provide continuous cooling over the entire operating range. Two types of dilution refrigerators exist; ^{3}He circulating and ^{4}He circulating. Adapting the former to space requires the physical control of three fluid interfaces[8]: two vapor-liquid interfaces and a liquid-liquid interface in the mixing chamber. The ^{4}He circulating type has similar difficulties. In both types liquid-liquid interface presents the biggest problem because the surface tension is extremely low.

There is an alternative technology to liquid based sub-kelvin coolers. These are demagnetization coolers. These coolers are inherently gravity independant. Small units of the size and power suitable for space use have been ground tested in various laboratories and a full IR detector/magnetic cooler system has been tested at Mt. Palomar[9]. The remaining issues relate to developing light weight, compact shielding, to prevent the degradation of the solid refrigerants, and to developing techniques to fabricate a space qualifiable cooler while keeping the parasitic heat loads small[10].

ALTERNATE TECHNOLOGIES

Technology	Status	Issues
Demagnetization coolers	Ground demonstrated	Magnetic shielding, interactions with neighboring experiments, parasitic heat, space qualification

SUMMARY

Many of the issues raised here can be resolved by a ground based development program. There are, however, a few items that are difficult or impossible to adequately demonstrate on the ground. These items all relate to the behavior of liquid helium in the low gravity environment of space. These are summarized in the chart below.

SUMMARY
LIQUID HELIUM MICRO-G FLUID MANAGEMENT ISSUES

Technology	Issue
Storage	Bulk fluid behavior and interactions with pointing; liquid management devices; in space conversion to superfluid
^{3}He refrigerators	Liquid retention with heat transfer
Dilution refrigerators	Phase separation of multiple fluid interfaces

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OVERVIEW

FLUID ACQUISITION AND TRANSFER

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This brief overview introduced the symposium session on microgravity fluid acquisition and transfer. It states the objective of NASA efforts in this technology and the approach being taken in the technology program. The problems are outlined and various methods for low-gravity fluid acquisition and transfer are summarized. Applications for the technology are described and an assessment of the current state of the art is presented. NASA and DoD on-going and planned programs are listed.

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INTRODUCTION

The overall objective of NASA efforts in microgravity fluid management is to develop the technology required for efficient fluid systems in space. The technology is applicable to both cryogenic and space-storable liquids, but current research emphasizes technology for managing cryogenic propellants, since there is little proven technology for in-space handling of cryogens. The research efforts include analysis, computer code development, and experiments. Verification of the anlytical models and the codes is an important element of the program.

This session of the symposium emphasizes issues pertaining to liquid acquisition and transfer in microgravity, although many of the papers present research results that are equally important to in-space fluid storage. The term "acquisition" encompasses all methods for positioning the liquid contents of a storage tank at the tank outlet and ensuring vapor-free extraction of the liquid. "Transfer" includes all aspects of filling one tank (e.g., a vehicle propellant tank or a storage tank) from another while in orbit.

Low-Gravity Fluid Acquisition and Transfer Technology

Overall Objective:	Provide technology to enable design of efficient systems for managing fluids in the space environment
General Approach:	Perform experiments to verify analytical models and scaling techniques

Acquisition = Positioning liquid at the tank outlet for withdrawal

Transfer = On-orbit tank fill or refill. Includes:

- Supply tank pressurization
- Receiver tank pressure control
- Chilldown
- Venting

Figure 1

APPLICATIONS

Applications for microgravity fluid management technology will include (1) propellant management in launch vehicle upper stages and orbiters; (2) on-orbit fueling of satellites and propulsion stages (including the Orbital Maneuvering Vehicle and the Orbital Transfer Vehicle), so they can be designed for launch without the loads associated with on-board propellant and/or for space-based reuse; (3) replenishing fluid subsystems on the Space Station; (4) resupplying propellant and other liquid consumables on space experiments and satellites to extend their service lives; and (5) supplying the liquids required for operation of space-based lasers, particle beam weapons, and other military platforms.

Potential Applications

- Earth-to-orbit transport vehicles
- On-orbit fueling of satellites and propulsion stages
- Space Station subsystems replenishment
- Experiment and satellite fluid resupply
- Resupply of reactants, fuels, coolants, and propellants for space-based directed-energy weapons

Figure 2

FLUID ACQUISITION AND TRANSFER METHODS

Many methods exist for liquid acquisition in low gravity and several have been demonstrated in practice. Some are used routinely in operational vehicles and satellites. The needs for further research and development rest principally in the areas of cryogenic fluid management and systems reusability. Four general approaches to liquid acquisition that are suitable for cryogens are (1) propulsive settling, (2) start baskets, (3) screened channels, and (4) vanes. The first two are applicable to vehicles and the last two to microgravity fluid transfer. The design of acquisition devices is particularly difficult for liquid hydrogen, because of its low surface tension and relative ease of vaporization.

Screened channels forming what is called a total-communication liquid acquisition device will likely be the approach used in on-orbit cryogen storage tanks. Vane systems cannot reliably position low-surface-tension fluids in the presence of disturbances. No significant low-gravity acquisition and transfer data has yet been obtained for liquid hydrogen and oxygen.

Liquid Acquisition

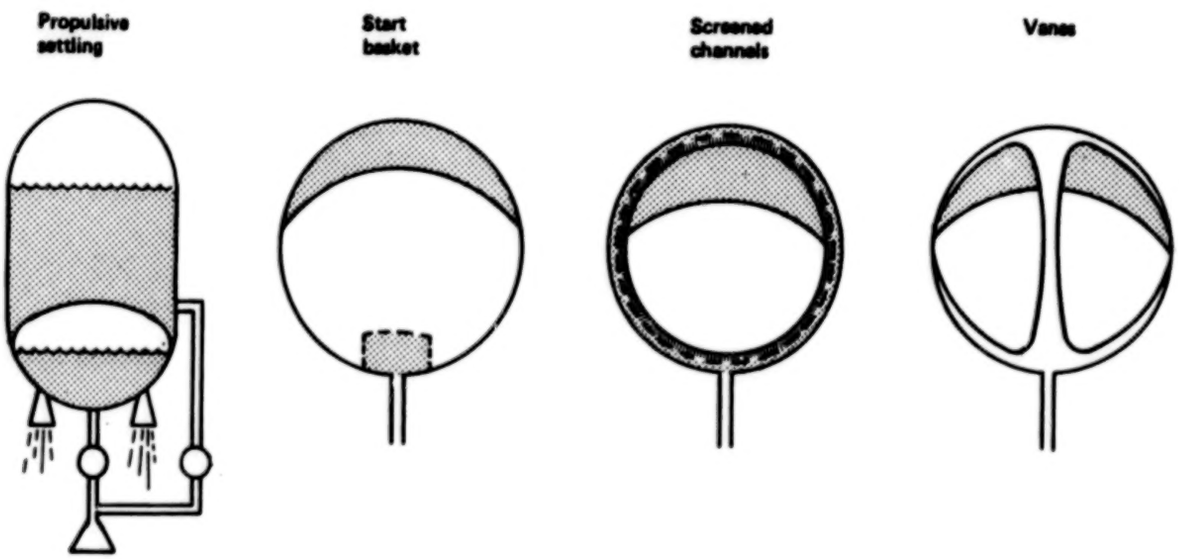

Figure 3

Methods for fluid transfer in microgravity can be classified as one of two general approaches: fluid dynamic or thermodynamic. The difference between them is in how the problem of venting the receiver tank ullage is handled. With the fluid dynamic approach, small acceleration forces (e.g., from vehicle drag, tethering, or small thrusters) or surface-tension liquid positioning devices are used to orient the liquid contents of the tank away from the vent. The liquid inflow rate must be small to avoid breaking up the liquid-vapor interface.

With thermodynamic approach, the ullage is compressed and condensed using the cool incoming liquid as a heat sink for the heat of condensation. This is the favored approach for cryogens. It avoids the need for venting during all but the chilldown phase of the transfer process. With a tank that is initially empty and warm, first a small amount of liquid is admitted to the tank, allowed to vaporize and chill the tank, and then vented.

Fluid Transfer

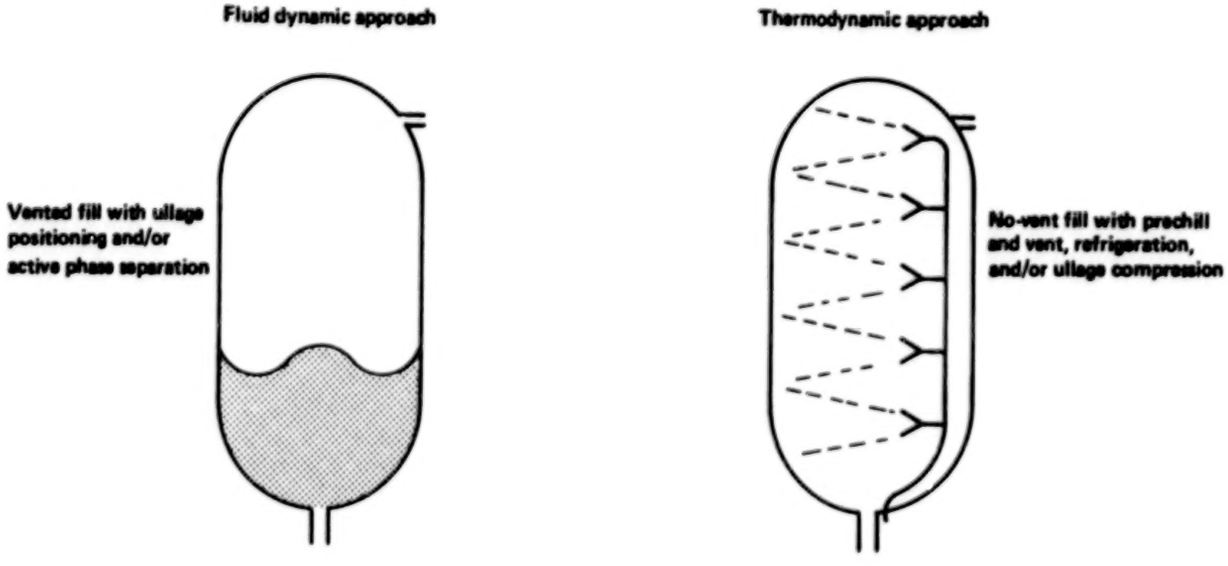
Fluid dynamic approach
Thermodynamic approach
Vented fill with ullage positioning and/or active phase separation
No-vent fill with prechill and vent, refrigeration, and/or ullage compression

Figure 4

STATE OF THE ART

The state of the art in liquid acquisition comprises space-proven, operational components for noncryogenic liquids but only unproven concepts for cryogens. Some normal-gravity laboratory tests have been conducted with small-scale cryogen systems. Microgravity flight experience with cryogen surface-tension liquid acquisition devices, slosh control, autogenous tank pressurization systems, and mass gaging is virtually nonexistent. Numerical modeling capability for microgravity fluid motion and thermodynamics is under development. One code developed for the NASA Lewis Research Center (called NASA-VOF2D) has just become available.

State-of-the-Art Assessment – Liquid Acquisition

- Surface-tension liquid acquisition devices
  - Flight experience with noncryogenic liquids (no performance data)
  - Small cryogenic system tests and screen characterization studies conducted in laboratory environment
- Fluid dynamic behavior
  - Some limited flight experience
  - Analytical correlations based on drop tower experiments
  - Numerical modeling capability under development
- Pressurization systems
  - Orbital data has been used to establish correlating parameters for high liquid outflow rate helium pressurant systems
  - Limited experience with autogenous pressurant systems
- Mass gaging instrumentation
  - Flight experience with noncryogenic liquid
  - Seek and develop activity underway at JSC

Figure 5

On-orbit transfer of a noncryogenic liquid (hydrazine) has been demonstrated on the Shuttle, and an operational system is under development at the Johnson Space Center (JSC) as part of the Orbital Spacecraft Consumables Resupply Systems program. Considerable activity is underway at NASA in conjunction with the Space Station program and within the military (e.g., the spacecraft Assembly, Maintenance, and Servicing study) to identify systems requirements for fluid resupply operations and to develop the necessary automation and robotics.

For cryogens, the data available is nearly all from ground-based testing. Some small-scale low-gravity data for liquid nitrogen was obtained in the NASA LeRC 5-second drop tower. On orbit test data for tank chill, no-vent fill, autogenous pressurization, fluid metering, line connect and disconnect, and leak detection are necessary.

State-of-the-Art Assessment – Fluid Transfer

- Transfer line and receiver tank chilldown
  - Analytical models and experimental data available for cryogen systems in normal gravity
  - Limited data obtained with LN_2 in NASA drop tower
- No-vent fill
  - Limited IR&D laboratory testing performed
- Fluid mass and quality metering
  - Limited cryogenic IR&D laboratory testing performed
- Quick disconnect
  - Development activity for space application, including instrumentation for leak detection, recommended by SSTSC

Figure 6

NASA AND DOD PROGRAMS

Several NASA and Department of Defense research programs and studies are addressing issues pertaining to microgravity fluid management. Few of them involve hardware at present, but many are concept and design studies intended to evolve into hardware development.

The NASA Cryogenic Fluid Management Flight Experiment program, for example, is currently designing a sophisticated space experiment for demonstrating technology and methods for storing and transferring liquid hydrogen. Studies of space tethers and of shuttle external tank propellant scavenging may lead to space experiments relatively soon. The Space Infrared Telescope Facility will require helium and propellant resupply. Two-phase thermal transport loops for the Space Station require technology for fluid handling. The Air Force Rocket Propulsion Laboratory is beginning a hardware development program for toroidal tanks for cryogenic upper stages and is planning a fluid management space experiment.

Current and Planned Programs - NASA and DOD

- Cryogenic Fluid Management Flight Experiment
- Orbital Transfer Vehicle
- Orbital Maneuvering Vehicle
- Shuttle propellant scavenging
- Space tethers
- Space Infrared Telescope Facility
- Mass gaging
- Space Station thermal control technology
- Storable Fluid Management Demonstration
- Orbital Spacecraft Consumables Resupply Systems
- Long-Term Cryogen Test Bed
- Helium Transfer Experiment
- Compact LOX Feedsystem (RPL)
- Fluid Management Flight Experiment (RPL)

Figure 7

SUMMARY

The needs for acquiring data on fluid behavior in microgravity and to demonstrate concepts and technology are well characterized. Some ground testing is on-going at NASA, in the military, and in industry, but normal-gravity experiments cannot in many circumstances adequately simulate important microgravity phenomena.

The papers in this section describe several current studies intended to lead eventually to space experiments. Among the topics covered are numerical modeling, fluid slosh and fluid-vehicle dynamic interaction, mass gaging, jet mixing and ullage condensation, the Cryogenic Fluid Management Flight Experiment, and methods for managing superfluid helium in microgravity.

References

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THE COUPLED DYNAMICS OF FLUIDS AND SPACECRAFT IN LOW GRAVITY

AND

LOW GRAVITY FLUID MEASUREMENT

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The very large mass fraction of liquids stored on board current and future generation spacecraft has made critical the technologies of describing the fluid-spacecraft dynamics and measuring or gauging the fluid. Combined efforts in these areas are described, and preliminary results are presented.

The coupled dynamics of fluids and spacecraft in low gravity study is characterizing the parametric behavior of fluid-spacecraft systems in which interaction between the fluid and spacecraft dynamics is encountered. Particular emphasis is given to the importance of nonlinear fluid free surface phenomena to the coupled dynamics.

An experimental apparatus has been developed for demonstrating a coupled fluid-spacecraft system. In these experiments, slosh force signals are fed back to a model tank actuator through a tunable analog second order integration circuit. In this manner, the tank motion is coupled to the resulting slosh force. Results are being obtained in 1-g and in low-g (on the NASA KC-135) using dynamic systems nondimensionally identical except for the Bond numbers.

The low gravity fluid measurement study is developing a radio frequency measurement technique, an inductive gauging technique, and an ultrasonic point measurement method. The radio frequency gauging technique measures the total fluid volume inside a tank by measuring the dissipation of electromagnetic waves within the fluid. The inductive gauging technique measures the total inductance of the fluid inside the tank which depends only on the volume of fluid contained. The ultrasonic point measurement technique measures total local fluid free surface height through the return time of a reflected ultrasonic wave.

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INTRODUCTION

Many current and future spacecraft designs require that large volumes of fluids be carried for long periods in low gravity for

- Propellant resupply
- Spacecraft attitude control
- Orbital maneuvers

Two critical technologies being studied include

- The interactive or coupled dynamics between the stored fluid and the spacecraft motion
- High accuracy measurement and gauging techniques for observing the amount, orientation, and quality of the fluid

The research effort includes complimentary experimental and analytical programs consisting of

- An apparatus for studying a couple fluid–spacecraft dynamic system
- Unique measurement and gauging hardware

COUPLED DYNAMICS OF FLUIDS AND SPACECRAFT

Problem Motivation

- Large mass fractions of stored liquids on board spacecraft in low gravity (>50% liquid)
- Controller bandwidths which include many fluid slosh modes
- Low frequency spacecraft modes such as flexible and libration modes

Research Features

- Provides experimental investigation of fluid–spacecraft coupling
- Imposes a coupled system by matching masses and frequencies
- Uses a generic modei tank and a simple type of spacecraft motion (cylinder and 1–DOF lateral spacecraft mode)
- Studies large amplitude responses
- Includes a broad parametric space
- Studies Bond number, viscosity scaling and contact angle hysteresis effects

Problem of Interest

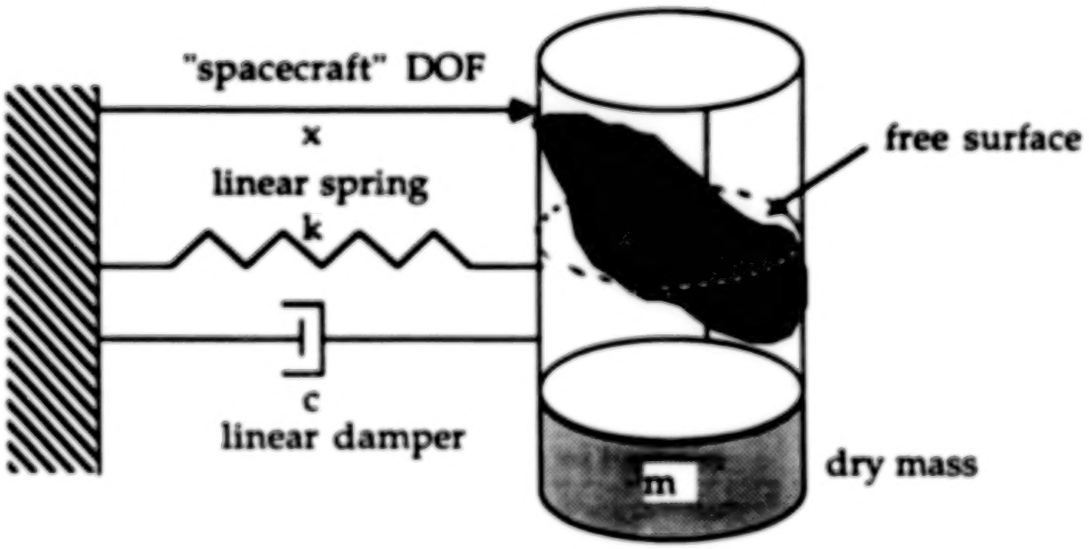


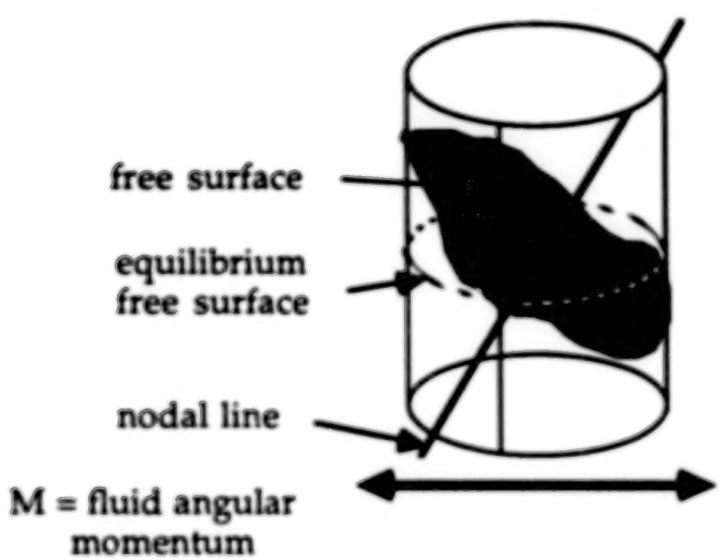
Figure 1

Nonlinear Effects in Fluid Slosh

An interactive or coupled system can result in large amplitude fluid slosh motion. Even small amplitudes of excitation near a slosh resonance can lead to nonlinear fluid slosh effects.

Nonlinear fluid slosh can lead to nonlinear effects in the spacecraft dynamics. Understanding these effects is important in determining the actual motion of the coupled system.

Four Possible Nonlinear Fluid Slosh Modes



M=0	1. planar harmonic (stationary nodal line)
M>0	2. nonplanar harmonic (rotating nodal line)
	3. limit cycle (swirl)
	4. chaotic (deterministic nonperiodic motion)

Which motion is excited depends upon the frequency of the excitation, the amplitude of the excitation, the amount of damping, and the initial conditions.

Figure 2

Overview of Experimental Effort

An apparatus has been developed which imposes in a controlled fashion coupling between the slosh with a model tank and a lateral spacecraft mode.

- Lateral slosh forces measured by a sensitive reaction balance
- Tank moved laterally by an electromagnetic shaker/servo
- Slosh force signal fed back to the shaker through a second order analog spacecraft mode circuit, thus coupling the slosh to the motion of the tank

The spacecraft mode circuit can be tuned to simulate a wide range of coupled systems. Spacecraft modal mass, frequency, and damping can be adjusted independently.

Block Diagram of the Closed Loop Slosh Coupling System

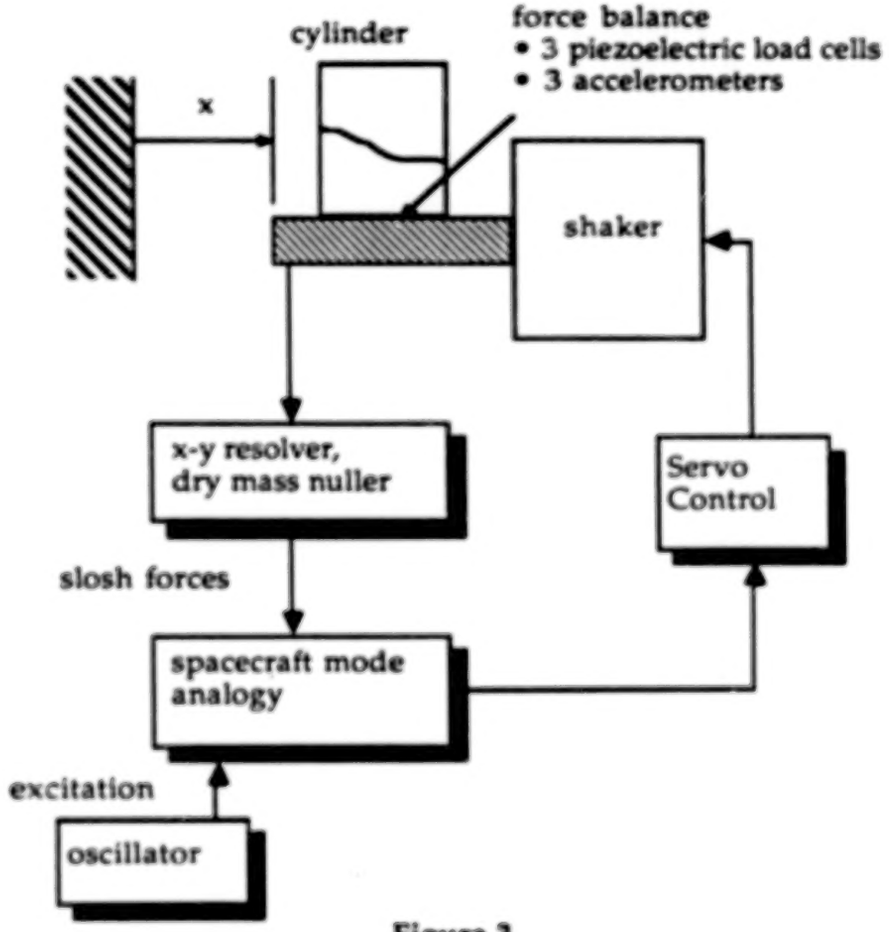


Figure 3

The response of the system is measured by the following quantities

- Slosh force
- Free surface motion
- Spacecraft mode amplitude (tank displacement)

The experiment varies the following nondimensional variables

- Bond number
- Mass ratio (fluid mass / spacecraft mass)
- Natural frequency ratio (fundamental slosh frequency / spacecraft modal frequency)
- Spacecraft modal damping rate

The Bond number is changed keeping the viscous scaling parameters constant by using the same diameter tank in

- 1–g capillary scaled experiments
- 0–g KC-135 experiments

In both cases, the large amplitude slosh of the fluid when not coupled to the spacecraft mode is also examined.

1–g Test Results

For the 1–g laboratory tests, a coupled system is studied using a steady harmonic excitation.

- Excitation frequency varied from below the fluid resonance to above the spacecraft mode resonance
- Excitation amplitude varied by a factor of 1 through 10 and the frequency sweep is repeated
- The response at resonance is plotted as a function of excitation amplitude
- Nonlinear effects are observed, as shown in Figure 4

Typical 1–g Results: Amplitude at Resonance as a Function of Input Amplitude

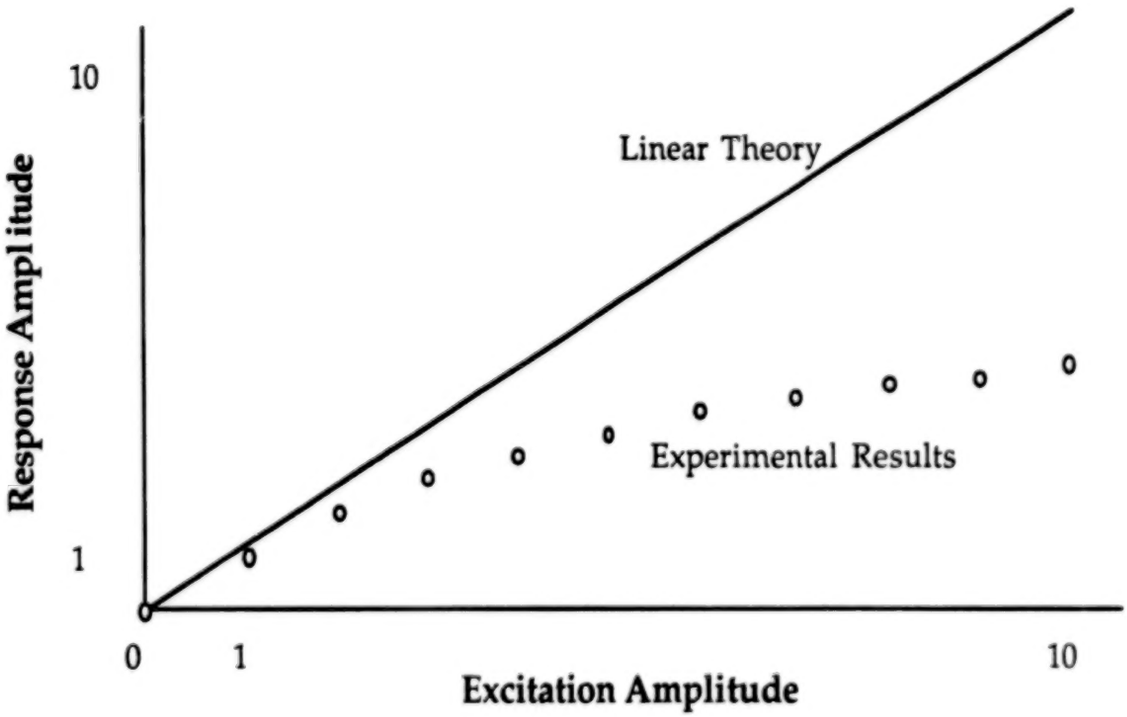


Figure 4

0–g KC–135 Tests

- Flown over 200 parabolas
- Use same diameter tank as in 1–g tests
- Isolates gravity effects

Issues

- Critical Bond number free surface instabilities
- Effects of small g level perturbations (0.03 gees rms typical)
- Data collected per parabola

Approach #1: Frequency Sweeps as in 1-g Tests

- Long time constant g level variations affect FFT output due to slosh natural frequency variation with g level
- Observe much higher fluid slosh damping than in 1-g

Approach #2: Pulse Ringdowns

- Pulse at various amplitudes and observe free decay
- Pulse 3 times per parabola and 1 time during 1.7 gee pullup
- Repeat tests for 2 parabolas to test repeatability
- Post flight data processing involves sophisticated ringdown system identification algorithms

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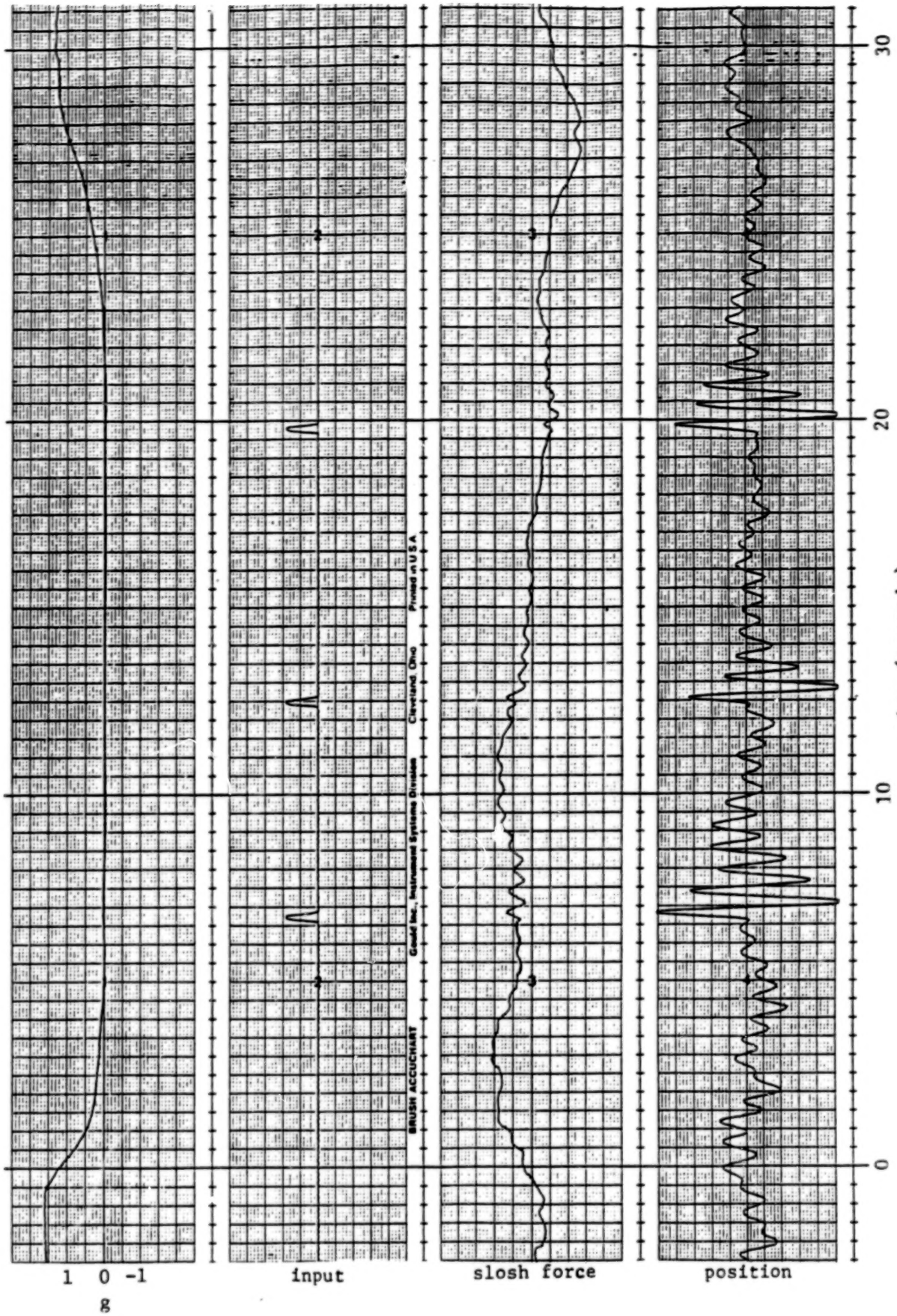


Figure 5 Typical Parabolic Flight Data

Preliminary Comparison of 1–g and 0–g Results

Uncoupled Large Amplitude Slosh Results

- Changing the Bond number to near 0 greatly increases fluid damping
- Moderate Bond number (1–g): See many nonlinear effects
  - Bi–stable modes
  - Periodically modulated slosh
  - Rotary slosh
  - Chaos
- Low Bond number (0–g): See fewer nonlinear effects due to increased damping
  - Increasing equivalent damping with excitation amplitude
  - Other effects suppressed

Coupled System Test Results

- Moderate Bond number (1–g)
  - Good degree of coupling
  - Amplitude dependence
  - Higher harmonics
  - Rotary slosh suppressed due to coupling
- Low Bond number (0–g)
  - Fluid is well behaved and is an efficient damper
  - Less coupling (due to less slosh mass?)
  - More mass ratio dependent than frequency ratio dependent in the ranges investigated so far
  - See simple nonlinear behavior

LOW GRAVITY FLUID MEASUREMENT

Measure

- Quantity
- Flow
- Position
- Quality

Fluids

- Storable propellants
- Cryogenics (O_2, H_2, He)
- Water
- Coolant
- Solar dynamic working fluids

Gauging Approaches under Development

- Radio frequency absorption
- Ultrasonic point measurement
- Inductive

Low Gravity Fluid Measurement Considerations

Low-g

- Ambiguous orientation
- Ambiguous density (trapped bubbles)
- Capillary effects

Cryogenics

- Low temp operation
- Phase change

Environment

- Radiation
- Vacuum
- Vibration/acceleration
- Chemical

Operational Constraints

- Safety
- Weight
- Size
- Size
- Complexity/Reliability
- Cost

Radio Frequency Gauging

Fluid quantity is measured by the dissipation of electromagnetic waves inside of the tank due to absorption by the fluid

- $Q = \frac{\text{Energy Stored in Tank}}{\text{Power Dissipated in Tank}}$

- Q can be related to fluid quantity

- $Q = \frac{\text{Resonant Frequency}}{\text{Full Width at Half Maximum of Resonance}}$

- Q can be measured by resonance width techniques

- If the electric field strength is uniform within the cavity (TEM modes) then the measurement is insensitive to fluid orientation

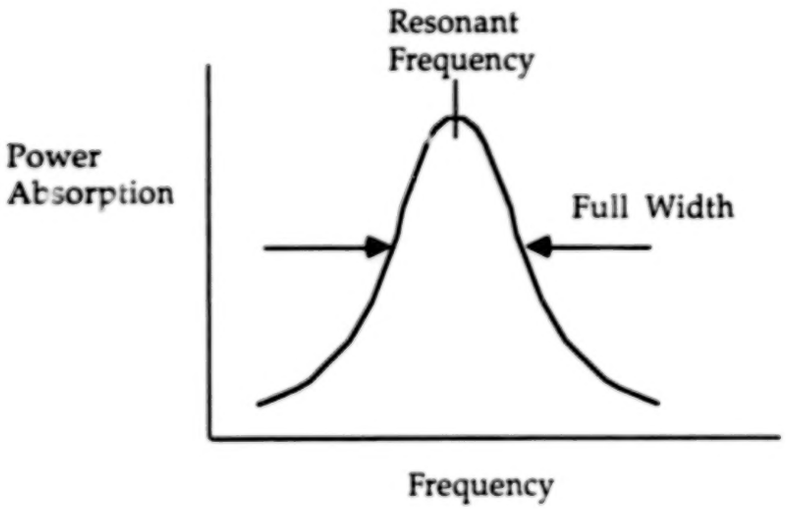


Figure 6

Schematic of Typical Resonance Width Gauging Set Up

Power is transmitted from an oscillator into the tank at various frequencies. On resonance, the power passes into the tank. Off resonance, the power passes back towards the oscillator. By monitoring the reflected power (voltage standing wave ratio) as a function of frequency, the quality factor Q may be inferred. Q can be related to the fluid quantity.

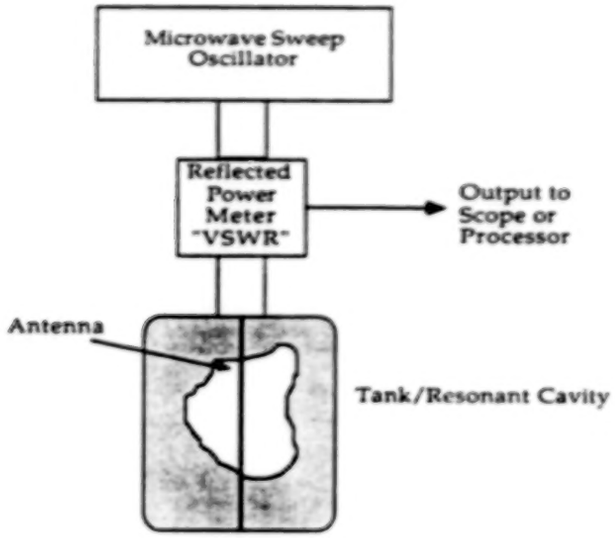


Figure 7

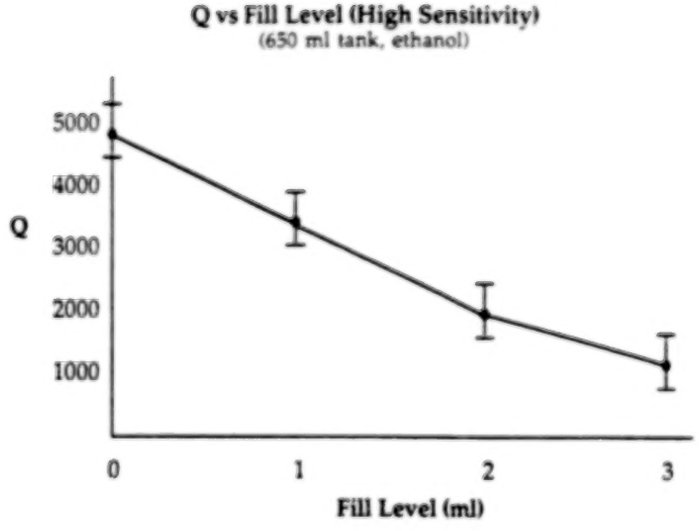


Figure 8

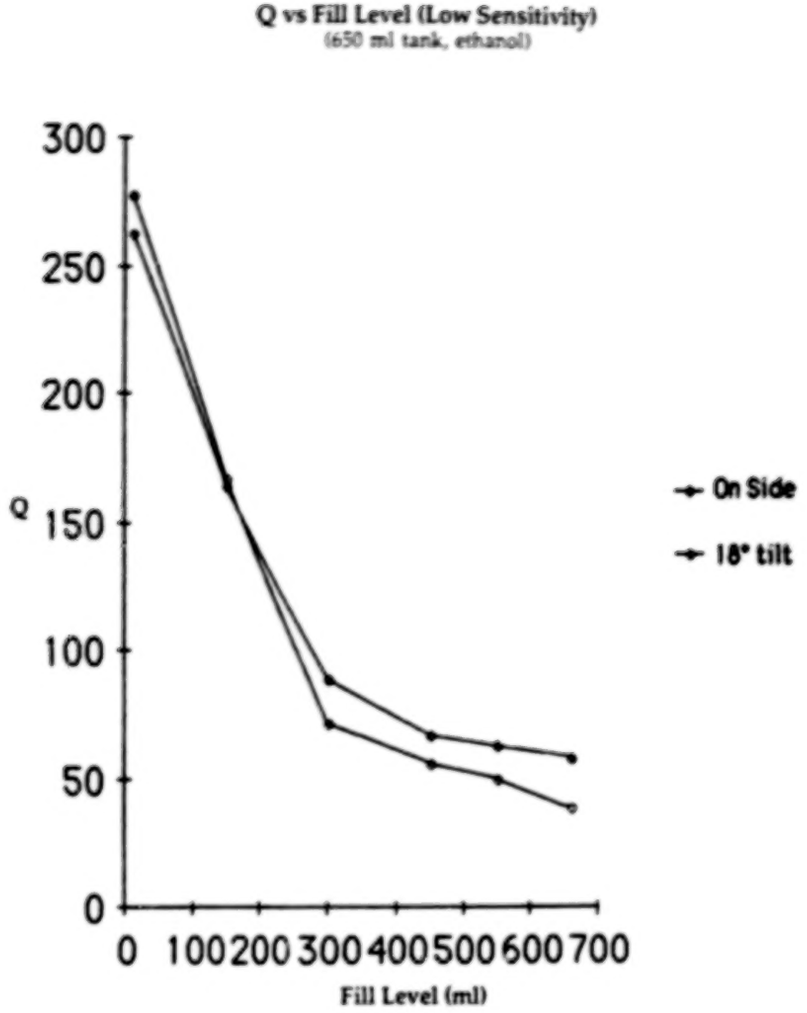

Q vs Fill Level (Low Sensitivity)
(650 ml tank, ethanol)
300
250
200
Q 150
100
50
0
0 100 200 300 400 500 600 700
Fill Level (ml)
On Side
18° tilt

Figure 9

Ultrasonic Point Measurement

- Individual transducers measure thickness of fluid at specific points by line of sight techniques
- Transducers may be external to tank
- Requires "benign" fluid orientation for quantity gauging
- Potential applications

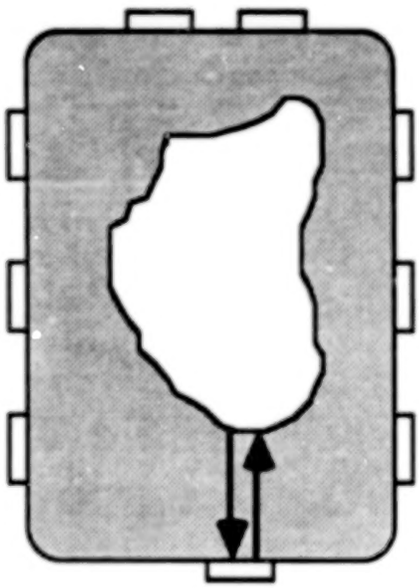
  Intermediate Bond numbers

  Specific geometries (eg. screen wall gap)

  Quality monitoring in pipes

  Slosh frequency identification

- Has been demonstrated in KC-135 tests by MIT and by MacDonald-Douglas



Ultrasonic Transducer

Figure 10

Free Surface Slosh Behavior of a Cylindrical Tank as Measured by the Ultrasonic Ranging Technique

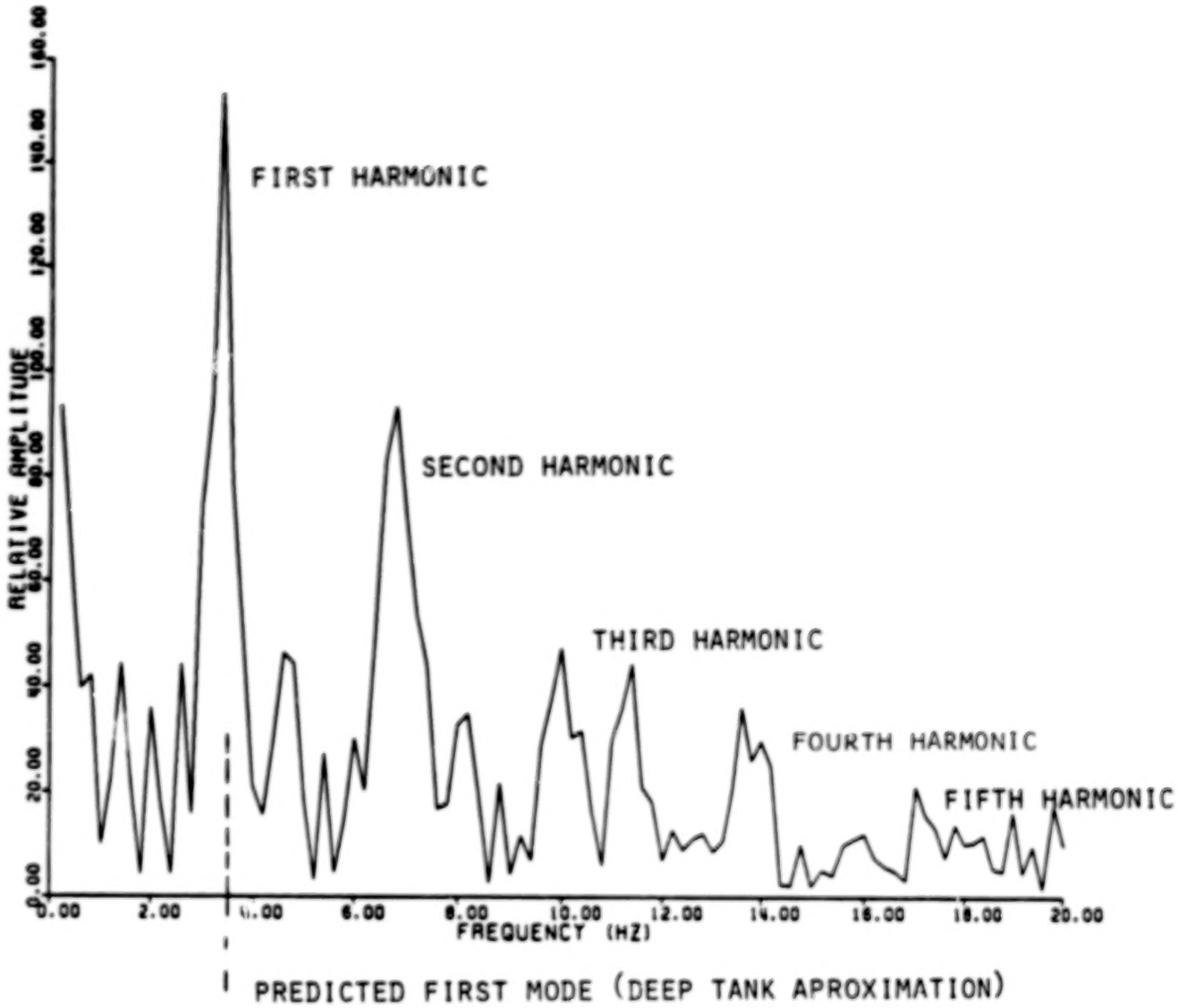


Figure 11

Inductive Gauging

- The magnetic inductance of a partially filled tank will depend on the quantity of high magnetic susceptibility fluid within the tank
- Liquid Oxygen has a high magnetic susceptibility
- The inductance can be measured by a coil which is external to the tank and can integrate over the entire tank volume
- Inductance and accuracy will increase with tank size
- In simple geometries the method is analytically insensitive to fluid orientation
- Preliminary experimental evaluation is underway

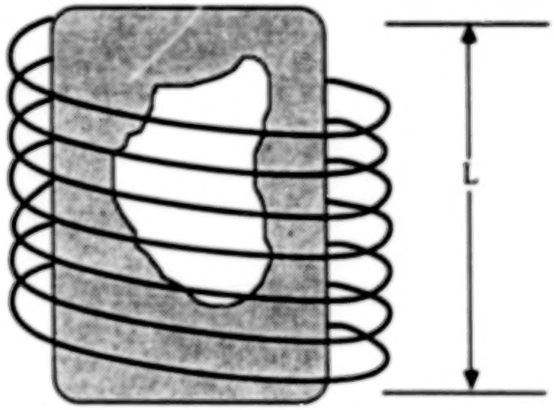


Figure 12

SUMMARY

Studying two critical technologies to large volume fluid management

- The interactive or coupled dynamics between the stored fluid and the spacecraft motion
- High accuracy measurement and gauging techniques for observing the amount, orientation, and quality of the fluid

Have developed

- An apparatus for studying a coupled fluid–spacecraft dynamic system
- Unique measurement and gauging hardware

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NUMERICAL MODELLING OF CRYOGENIC PROPELLANT BEHAVIOR IN LOW-G

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A partial survey is presented of recent research, sponsored by the NASA Lewis Research Center, into the computational modelling of cryogenic propellant behavior in a low gravity environment. This presentation is intended to provide insight into some of the specific problems being studied and into how these studies are part of an integrated plan to develop predictive capabilities. A brief description of the computational models developed to analyze jet induced mixing in cryogenic propellant tankage is presented along with representative results. Similar information is presented for a recent examination of on-orbit self-pressurization. A study of propellant reorientation has recently been initiated and preliminary results are included. The presentation concludes with a list of ongoing efforts and projected goals.

For recent survey of general program in reduced gravity fluid management technology sponsored by NASA LeRC, see Reference 4.

SOLA is an acronym for SOLution Algorithm. This is a general technique for solution of the NAvier-Stokes Equations which has been developed by the Los Alamos National Laboratory.

1. COMPUTATIONAL TECHNOLOGY
   - SOLA FAMILY
   - UNIQUE FEATURES OF NASA–VOF2D

2. JET INDUCED MIXING
   - CODE DEVELOPMENT
   - COMPUTATIONAL RESULTS

3. SELF–PRESSURIZATION
   - CODE DEVELOPMENT
   - COMPUTATIONAL RESULTS

4. REORIENTATION
   - PROGRESS REPORT

Figure 1

For code details, see Reference 9.

This code is a member of a family of SOLA Codes developed at LASL. Most are available through NSIC at Argonne National Laboratory.

NASA–VOF2D

DEVELOPED FOR LeRC BY THE LOS ALAMOS SCIENTIFIC LABORATORY (LASL) AS PART OF AN ONGOING INTERAGENCY AGREEMENT.

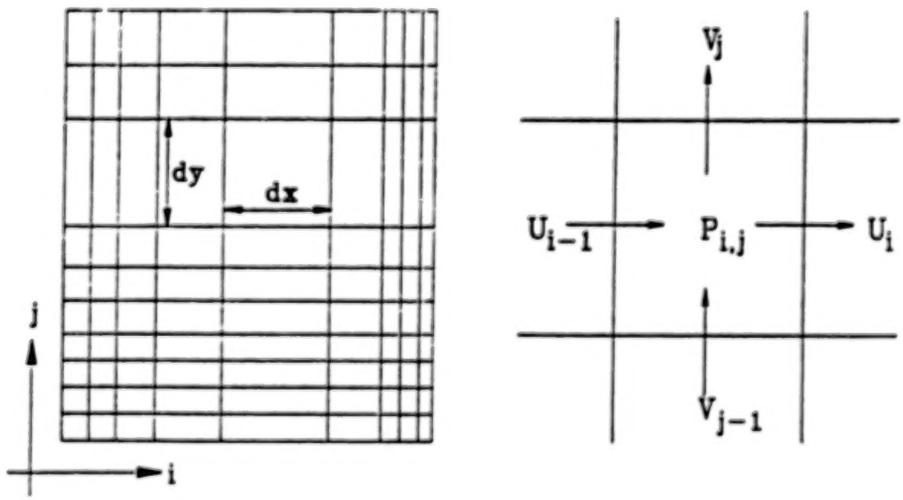
GENERAL DESCRIPTION:

- **TWO DIMENSIONAL (CARTESIAN OR CYLINDRICAL)**
- **EULERIAN MESH OF RECTANGULAR (ANNULAR) CELLS**
- **VARIABLE CELL SIZE (ROWS & COLUMNS)**
- **SOLUTION OF LAMINAR HYDRODYNAMIC PROBLEM**
- **STAGGERED GRID OF PRIMITIVE VARIABLES**

Figure 2

A variable mesh is essential for resolving features of different scales (i.e. boundary layers, mixing jets, bulk flows).

Variables are evaluated at either the center of the computational cell or at the middle of a cell face.



COMPUTATIONAL MESH STAGGERED GRID

Figure 3

C-2

For details, see Reference 7.

SOLUTION ALGORITHM (SOLA)

- EVOLVED FROM LASL SIMPLIFIED MARKER & CELL
- LASL HAS DEVELOPED A FAMILY OF SOLA CODES
- BASIC STEPS IN SOLUTION OF N–S EQUATIONS:

1. SOLVE AN EXPLICIT FINITE DIFFERENCE APPROXIMATION TO THE MOMENTUM EQUATIONS TO OBTAIN A FIRST GUESS FOR NEW–TIME–LEVEL VELOCITIES.
2. ITERATIVELY ADJUST CELL PRESSURES AND VELOCITIES TO SATISFY CONTINUITY AT THE NEW–TIME–LEVEL.

REPEAT STEPS 1 AND 2 TO MARCH THROUGH TIME.

Figure 4

The VOF Algorithm has evolved and improved with recent members of the SOLA family of codes.

The surface tension model is still under development. Flows with sharp corners, such as a geyser piercing a surface, are difficult to compute.

UNIQUE FEATURES:

VOLUME–OF–FLUID (VOF) METHOD

- REPLACES MARKER PARTICLES OF EARLIER LASL CODES
- CAPABLE OF MODELLING COMPLEX FREE SURFACES
- SPECIAL ALGORITHM TO MAINTAIN SHARP FEATURES

SURFACE TENSION MODEL

- COMPUTES SURFACE TENSION FORCE BASED ON CURVATURE OF FREE SURFACE
- IMPOSES EQUIVALENT PRESSURE USING AN INTER–CELL INTERPOLATION SCHEME
- PERFORMS SPECIAL CALCULATIONS AT INTERSECTION OF FREE SURFACE WITH A SOLID BOUNDARY TO COMPUTE WALL ADHESION FORCES.

Figure 5

Partial cell blockage is required for reorientation problems.

Tools include: zero-g equilibrium interface calculation, appropriate dimensionless variables, and non-aligned solid boundary definition routine.

PARTIAL CELL BLOCKAGE

LIMITED-POROSITY TECHNIQUE PROVIDES SIGNIFICANTLY IMPROVED MODELLING OF CURVED BOUNDARIES

ASSORTED TOOLS TO AID IN SETUP AND ANALYSIS OF PROBLEMS IN A LOW-G ENVIRONMENT

Figure 6

For details, see References 2 and 3.

MOTIVATION

THERMODYNAMIC VENT SYSTEM (TVS)

- CONCEPT: EXTRACT SACRIFICIAL FLUID, EXPAND THROUGH VALVE, USE COOLED LIQUID TO HELP CONTROL TANK PRESSURE
- PROBLEM: HOW TO DISPERSE COOLING EFFECT THROUGHOUT PROPELLANT POOL
- PROPOSED SOLUTION: JET INDUCED MIXING
- NEED: A TOOL TO PREDICT EFFECTIVENESS OF JET INDUCED MIXING IN DISPERSING COOLING EFFECT OF TVS

Figure 7

For details, see Reference 5.

SOLA-ECLIPSE

ENERGY CALCULATIONS FOR LIQUID PROPELLANTS
IN A SPACE ENVIRONMENT

BASELINE CODE: NASA SOLA-VOF (PREDECSSOR OF NASA-VOF2D)

MAJOR ADDITIONS TO BASELINE CODE REQUIRED TO ANALYZE JET INDUCED MIXING PROBLEM:

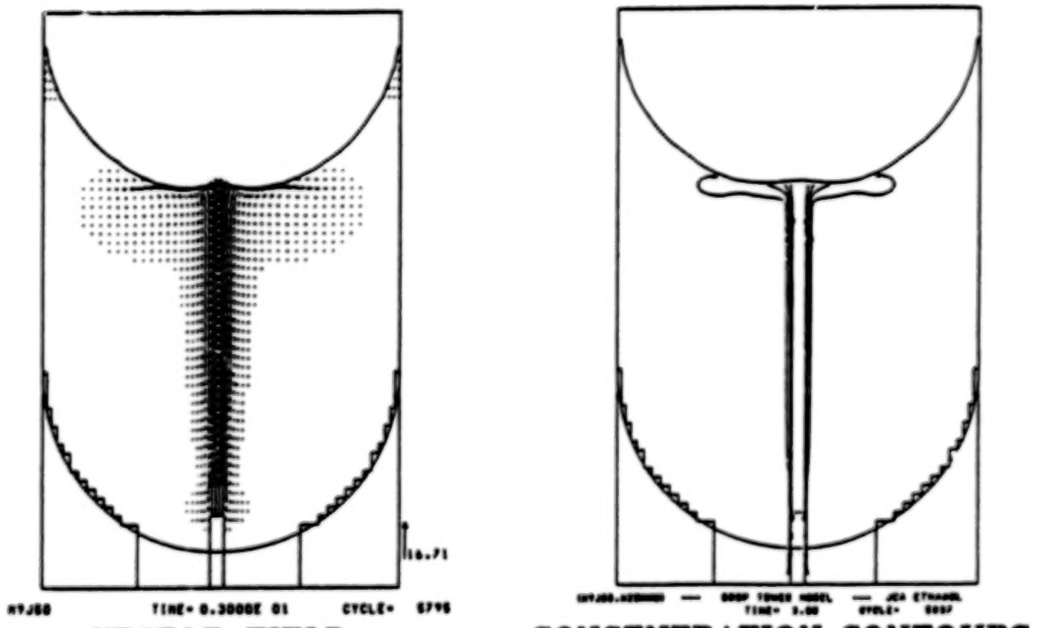
- ENERGY EQUATION
  CONDUCTION AND FORCED CONVECTION WITHIN THE LIQUID PHASE
- TURBULENCE MODEL
  TWO-EQUATION MODEL (k-e)
- NEW GRAPHICAL DISPLAY OPTIONS

Figure 8

Scale model experiments to investigate jet induced mixing were performed in the LeRC Zero-G Facility, (ZGF). Reference 2 reports the results of experiments which used ethanol in plexiglas tanks. Dyed ethanol was injected and high-speed photography was used to record the mixing. Approximately 3 seconds of mixing time is available in the ZGF.

As part of the code verification process, computationally predicted mixing was compared to the experimental results reported in Reference 2. Figure 9 shows computational predictions for a laminar jet in a 10 cm diameter tank.

There is a good match between computational predictions and experimental data.



VECTOR FIELD CONCENTRATION CONTOURS

SCALE MODEL TANK, LAMINAR JET AT 3 SEC.

Figure 9

Figure 10 shows computational predictions for a turbulent jet issuing into a a partially filled tank. This case was chosen from among the experimental results reported in Reference 2.

Again, there is a good match between computational predictions and experimental data.

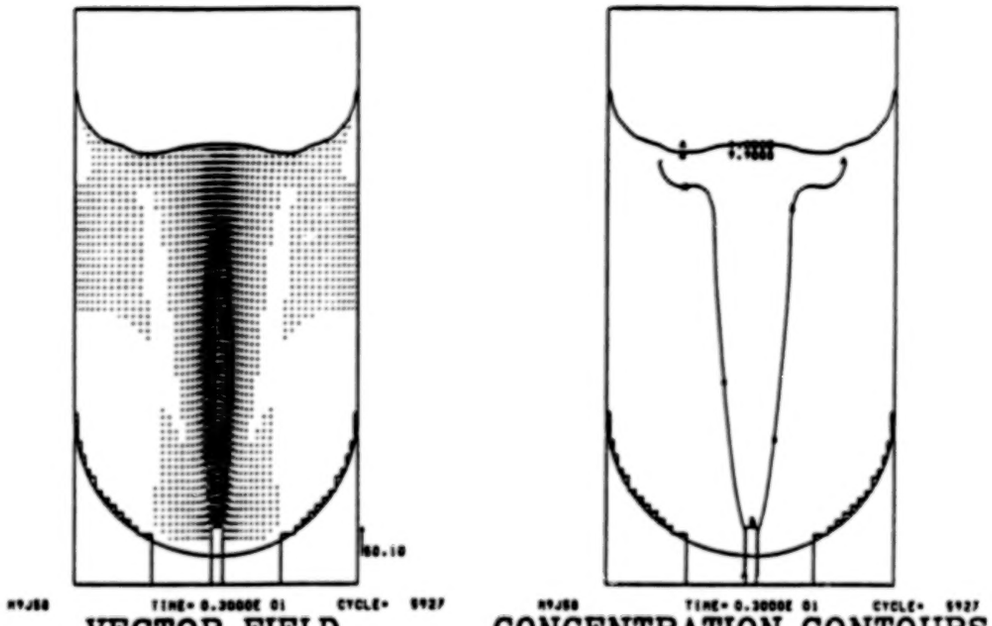
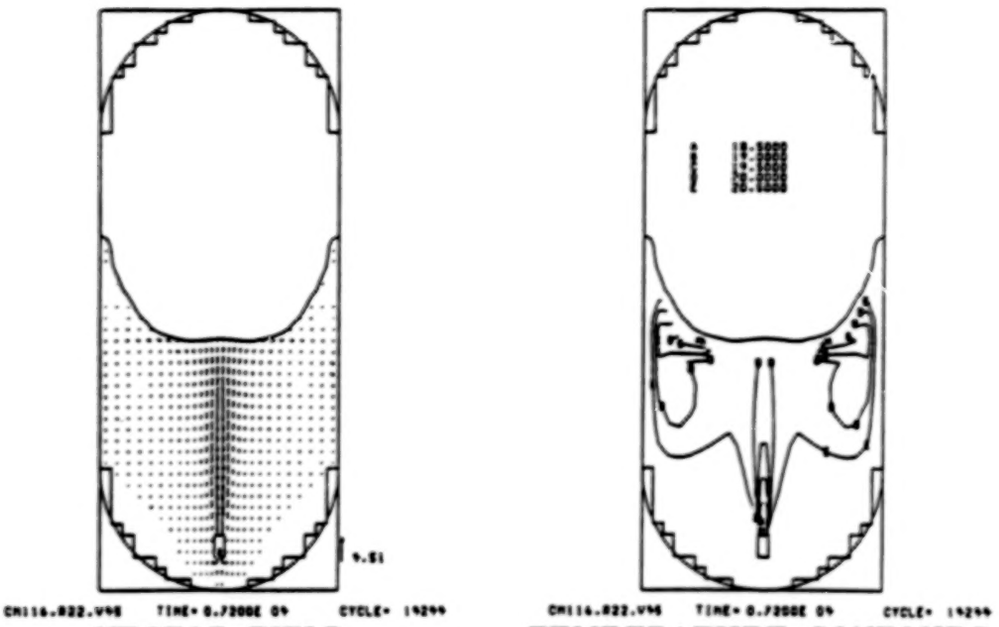


Figure 10

The axial jet appears to be capable of adequately mixing the propellant pool in a typical Orbit Transfer Vehicle, (OTV), tank.

Difficulties with the thermal model leave some questions as to accuracy of thermal results.



VECTOR FIELD TEMPERATURE CONTOURS

FULL SCALE TYPICAL OTV, TURBULENT JET AT 1 HOUR

Figure 11

For details, see Reference 5.

CONCLUSIONS

- VOF COMBINED WITH SURFACE TENSION MODEL IS CAPABLE OF MODELING THE JET MIXING PROBLEM PROVIDED THE JET GEYSER DOES NOT PIERCE THE FREE SURFACE.
- k–e TURBULENCE MODEL IS ADEQUATE FOR THE JET MIXING PROBLEM
- MORE WORK IS NEEDED ON LIQUID–LIQUID HEAT TRANSFER AT THE FREE SURFACE
- JET INDUCED MIXING APPEARS TO BE A VIABLE TECHNIQUE FOR DISPERSING THE COOLING EFFECT OF A TVS

Figure 12

For details, see Reference 6.

MOTIVATION

- THE NEED TO PREDICT THE SELF–PRESSURIZATION RATE OF CRYOGENIC PROPELLANT TANKAGE DURING PROLONGED EARTH ORBIT
- THE DESIRE TO MAXIMIZE PROPELLANT CONSERVATION DURING PROLONGED EARTH ORBIT

SPECIFIC QUESTION:

DOES INITIAL SUBCOOLING OF THE LIQUID PHASE SIGNIFICANTLY EFFECT THE SELF–PRESSURIZATION RATE OF A CRYOGENIC PROPELLANT TANK IN EARTH ORBIT?

Figure 13

For details of baseline code, see Reference 7.

For details of heat transfer and thermodynamic models, see Reference 6.

SOLA–ECLIPSE

BASELINE CODE: NASA–VOF2D

MAJOR ADDITIONS TO BASELINE CODE REQUIRED TO ANALYZE THE SELF–PRESSURIZATION PROBLEM:

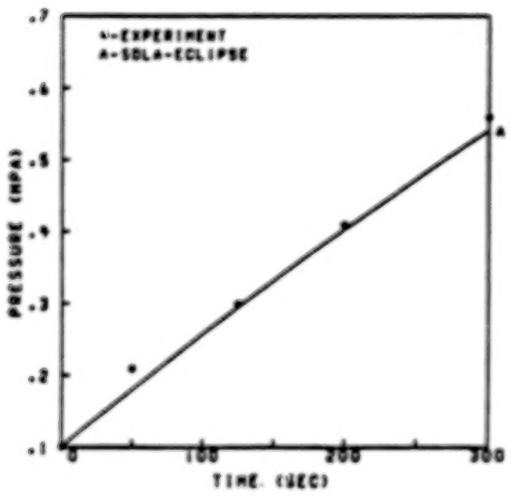
1. THERMODYNAMIC MODEL FOR THE VAPOR PHASE
2. THERMAL ENERGY EQUATION
   - SOLID–TO–LIQUID
   - LIQUID–TO–LIQUID
   - LIQUID–TO–VAPOR
   - SOLID–TO–VAPOR
3. PHASE CHANGE MODEL

Figure 14

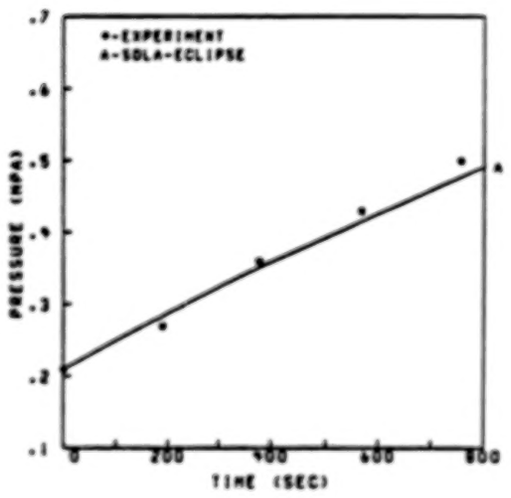
Reference 1 reports the experimental results used for evaluation of code performance.

There is good agreement between computational predictions and experimental data.

The accuracy of computational predictions breaks down for high heat flux rates that induce pool boiling.



Self-Press. (Unif.) (Dia=23cm) (1g)



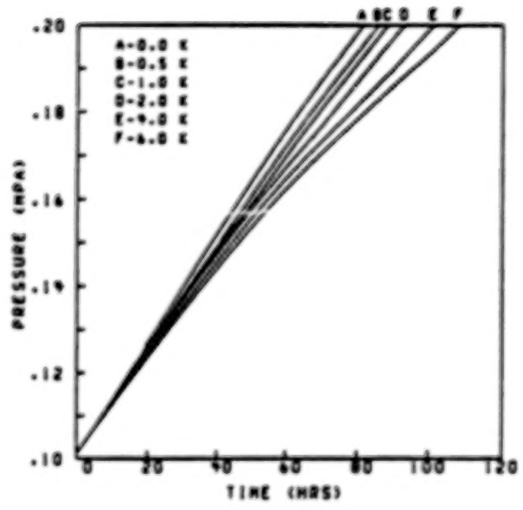
Self-Press. (Unif.) (Dia=23cm) (low-g)

SCALE MODEL TANKS, PREDICTIONS & EXPERIMENTAL DATA

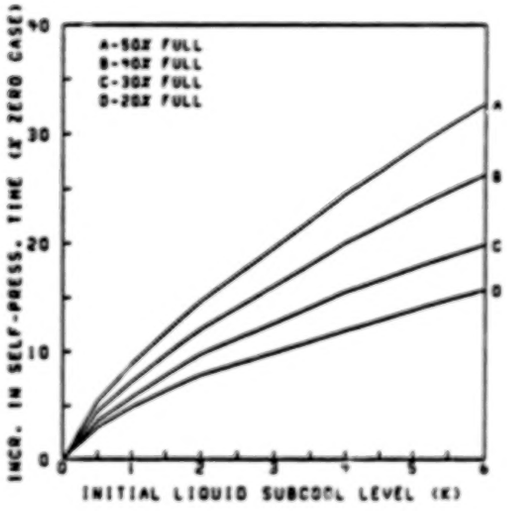
Figure 15

Figure 16 shows predicted self-pressurization rates for a typical OTV in earth orbit.

From the curves displayed in Figure 16, it is concluded that the effectiveness of subcooling in suppression of self-pressurization rate decreases with increased subcooling.



Pressure Rise in OTV Tank (50% Full)



Effectiveness of Subcooling

COMPUTATIONAL PREDICTIONS FOR OTV TANKS

Figure 16

CONCLUSIONS

- THE THERMODYNAMIC AND HEAT TRANSFER MODELS ARE ADEQUATE FOR PREDICTING SELF-PRESSURIZATION RATES FOR ON-ORBIT CRYOGENIC TANKAGE

- THE SELF-PRESSURIZATION RATE CAN BE SIGNIFICANTLY DECREASED THROUGH INITIAL SUBCOOLING OF THE LIQUID PHASE

- THE EFFECTIVENESS OF INCREMENTAL INCREASES IN INITIAL SUBCOOL LEVEL DIMINISHES WITH INCREASING LEVELS OF SUBCOOLING

Figure 17

MOTIVATION

THE DESIRE TO PREDICT BULK PROPELLANT MOTION DUE TO IMPOSED ACCELERATIONS WHICH ARE INTENDED TO POSITION THE LIQUID OVER THE TANK OUTLET PRIOR TO FIRING OF THE MAIN ROCKET ENGINES.

APPLICATIONS:

- OPTIMIZE NEW DESIGNS WITH RESPECT TO CONSERVATION OF PROPELLANT
- EVALUATE THE SUITABILITY OF EXISTING EQUIPMENT FOR NEW APPLICATIONS
- INVESTIGATE NOVEL APPROACHES AIMED AT MINIMIZING PROPELLANT EXPENDITURE

Figure 18

For details of NASA-VOF2D, see Reference 9.

NASA-VOF2D is the newest member of the SOLA family of codes.

Work on this problem is just beginning.

NASA–VOF2D

HOPEFULLY, ONLY MINOR CHANGES WILL BE REQUIRED IN ORDER TO RUN THE PROBLEMS OF INTEREST:

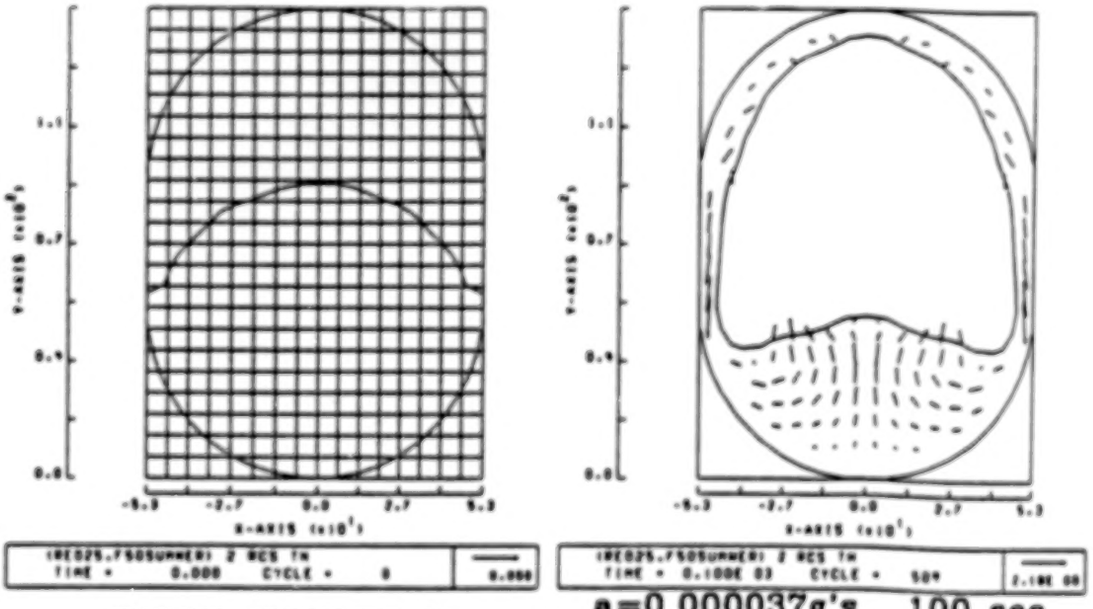
- TIME–DEPENDENT BOUNDARY CONDITIONS
- UNKNOWN AT THIS TIME BUT SURELY EXIST

Figure 19

The tank is a 1/4 scale model of typical OTV tank that has been proposed for the CFMFE.

This is the optimal acceleration level predicted for this configuration using the correlations presented in Reference 8.

There is reasonable agreement between computational predictions and correlations.



INITIAL CONDITION

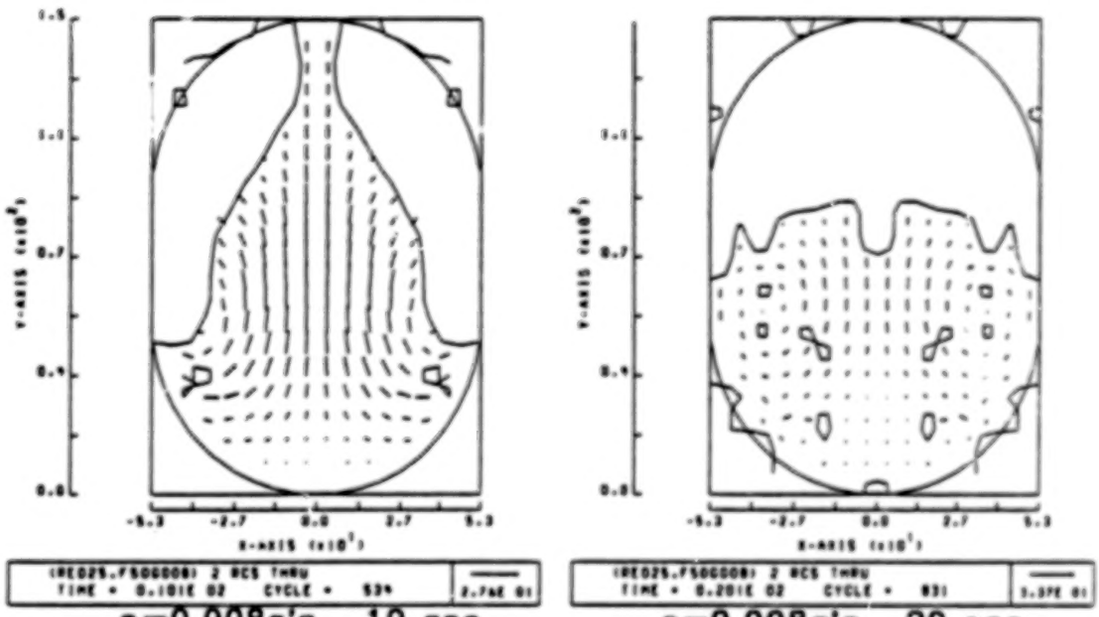
a=0.000037g's. 100 sec STEADY ACCELERATION

COMPUTATIONAL PREDICTIONS FOR 1/4 SCALE CFMFE TANK

Figure 20

This acceleration level corresponds to the firing of 2 Shuttle RCS thrusters.

Figure 21 presents computational predictions for the flow resulting from continuous thruster firing.



COMPUTATIONAL PREDICTIONS FOR 1/4 SCALE CFMFE TANK

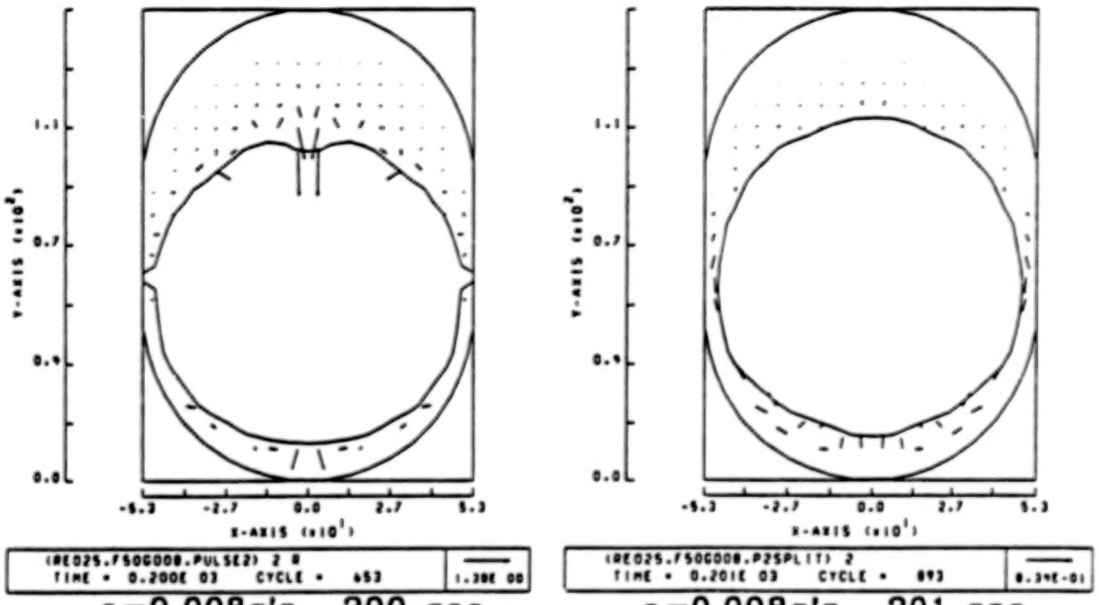
Figure 21

Figure 22 presents computational predictions for propellant motion due to intermittent thruster firing. The same total impulse is applied for both cases.

In the first case, the total impulse is applied through a single firing of the thrusters which occurs from t=0.0 until t=0.2 seconds.

In the second case, the total impulse is broken into two segments. The first thruster firing occurs at t=0.0 and has a duration of 0.1 seconds. The second firing occurs at t=0.1 seconds and also has a duration of 0.1 seconds.

Conclusion: there is a slight improvement with a split impulse.



a=0.008g's, 200 sec
dt=0.2 @ t=0.

a=0.008g's, 201 sec
dt=0.1 @ t=0., 100.

COMPUTATIONAL PREDICTIONS FOR 1/4 SCALE CFMFE TANK

Figure 22

THE FOLLOWING LIST PRESENTS SOME OF THE TASKS CURRENTLY BEING PERFORMED THROUGH THE SUPPORT OF NASA GRANT NAG3-578.

- ANALYSIS OF REORIENTATION PROCESS WITH PARTICULAR APPLICATION TO CFMFE.
- ADDITION OF CONVECTION AND TURBULENCE MODELS TO LATEST VERSION OF SOLA-ECLIPSE
- USER'S MANUAL FOR EXECUTION OF NASA-VOF2D IN THE LeRC COMPUTING ENVIRONMENT
- IMPROVED GRAPHICAL OUTPUT CAPABILITIES

A LONG RANGE GOAL OF THIS EFFORT IS TO MAKE THE SOLA-ECLIPSE CODE AVAILABLE THROUGH "COSMIC".

Figure 23

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MIXING-INDUCED FLUID DESTRATIFICATION AND ULLAGE CONDENSATION

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Boeing Aerospace Company
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Anthony Enterprises
Federal Way, Washington

In many applications, on-orbit storage and transfer of cryogens will require forced mixing to control tank pressure without direct venting to space. During a no-vent transfer or during operation of a thermodynamic vent system in a cryogen storage tank, pressure control is achieved by circulating cool liquid to the liquid-vapor interface to condense some of the ullage vapor.

To measure the pressure and temperature response rates in mixing-induced condensation, researchers at Boeing developed an experiment that uses Freon 11 to simulate the two-phase behavior of a cryogen. This is a normal-gravity experiment designed to provide thermal data to correlate with previous dye-mixing experiments. A thin layer at the liquid surface is heated to raise the tank pressure, and then a jet mixer is turned on to circulate the liquid, cool the surface, and reduce the pressure. Many nozzle configurations and flow rates are being used. Tank pressure and the temperature profiles in the ullage and the liquid are measured.

Initial data from this ground test are shown correlated with normal-gravity and drop-tower dye-mixing data. Pressure collapse times are comparable to the dye-mixing times, whereas the times needed for complete thermal mixing are much longer than the dye-mixing times. Results and experience from this experiment are being applied to the design of a microgravity experiment to be flown on the Space Shuttle.

INTRODUCTION

On-orbit storage and transfer of cryogenic fluids will be an increasingly important part of space operations. For example, the projected growth version of NASA's Space Station will require the storage and resupply of liquid nitrogen, oxygen, and hydrogen. The Orbital Transfer Vehicle will use liquid oxygen and liquid hydrogen propellants and will be refueled from storage tanks at the Space Station. Satellites and space platforms will be resupplied by tankers operating from the Space Station and orbiting fuel depots.

An understanding of mixing phenomena in low gravity is essential to the successful design of cryogenic storage and resupply systems. Forced mixing will be required during a no-vent fill to enhance condensation and reduce fill times. It may also be required in cryogen storage tanks to chill hot spots in the liquid, thereby reducing the vapor pressure.

Low-G Mixing

- On-orbit cryogen storage
  - Tank pressure depends on temperature of warmest liquid in tank
  - Compact heat exchanger/thermal vent system requires active mixing to distribute cooling evenly throughout tank
- On-orbit transfer of storable and cryogenic liquids
  - For many low-g applications, no-vent fill is attractive option
  - Active mixing in receiver tank collapses ullage, leading to much shorter transfer times

Figure 1

PREVIOUS TESTING

There have been several investigations of mixing phenomena over the past twenty years. These tests have been performed in normal-gravity and low-gravity conditions with a variety of fluids. Several different mixing criteria have been used, including dye observation, thermal measurements, and acid-base indicators. The following is a summary of these mixing tests.

- Lewis Research Center (LeRC) - J. C. Aydelott (ref. 1)
  - Drop tower and 1-g data
  - Visual observation of dye mixing in water
- Martin Marietta - S. M. Dominick (ref. 2)
  - 1-g tests
  - Freon 113 and Freon 11
  - Thermal data
- General Dynamics Fort Worth - L. J. Poth (ref. 3)
  - 1-g tests
  - Temperature measurements in water
  - Open and closed test tanks
- General Dynamics Convair - M. A. Wollen (ref. 4)
  - 1-g tests
  - Dye disappearance tests in water (neutralization of acid with base)
- Lockheed - B. R. Bullard (ref. 5)
  - 1-g tests
  - Condensation rates in closed tanks
  - Freon 12, Methane, LN_2, LH_2

CURRENT RESEARCH AT BOEING

Data on low-gravity fluid mixing are limited. The drop-tower data obtained by Aydelott are the most useful, although the scale of his experiments was necessarily small and the dispersion of dye in water needs to be related to thermal mixing in cryogens. Ground-test data on thermal mixing help in determining that relationship. However, bouyancy effects that are absent in low gravity are readily apparent in these data.

We have begun a two-part effort at the Boeing Aerospace Company to obtain additional data. The first part is a series of normal-gravity experiments using Freon 11 and a jet mixer. The second part is to be a Get-Away Special experiment on the Space Shuttle. Our principal objectives are to obtain design data for low-gravity fluid management systems and to help verify the NASA-ECLIPSE fluid motion and thermodynamics simulation code.

Cryogen Tank Pressure Control in Low Gravity

Boeing Aerospace Company IR&D

Objective:
- Determine mixing requirements for efficient pressure control in cryogen tanks
- Verify BAC and LeRC models of fluid destratification and ullage condensation

Rationale:
- Pressure control during thermodynamic vent system operation or during tank fill may require active mixing
- Low-gravity mixing data is lacking

Approach:
- Test a variety of mixer configurations on the ground, using saturated Freon to simulate cryogens, to provide detailed thermal profiles for validation of numerical model
- Perform low-gravity tests in STS Get-Away Special payload carrier

Figure 2

GROUND TEST OBJECTIVES

The objectives for our laboratory experiment are summarized in Figure 3 below. Our emphasis is on establishing a correlation between thermal-mixing and dye-mixing data. When computer models are verified with data from space experiments, it may be possible to extrapolate the more readily obtained normal-gravity data to low-gravity conditions.

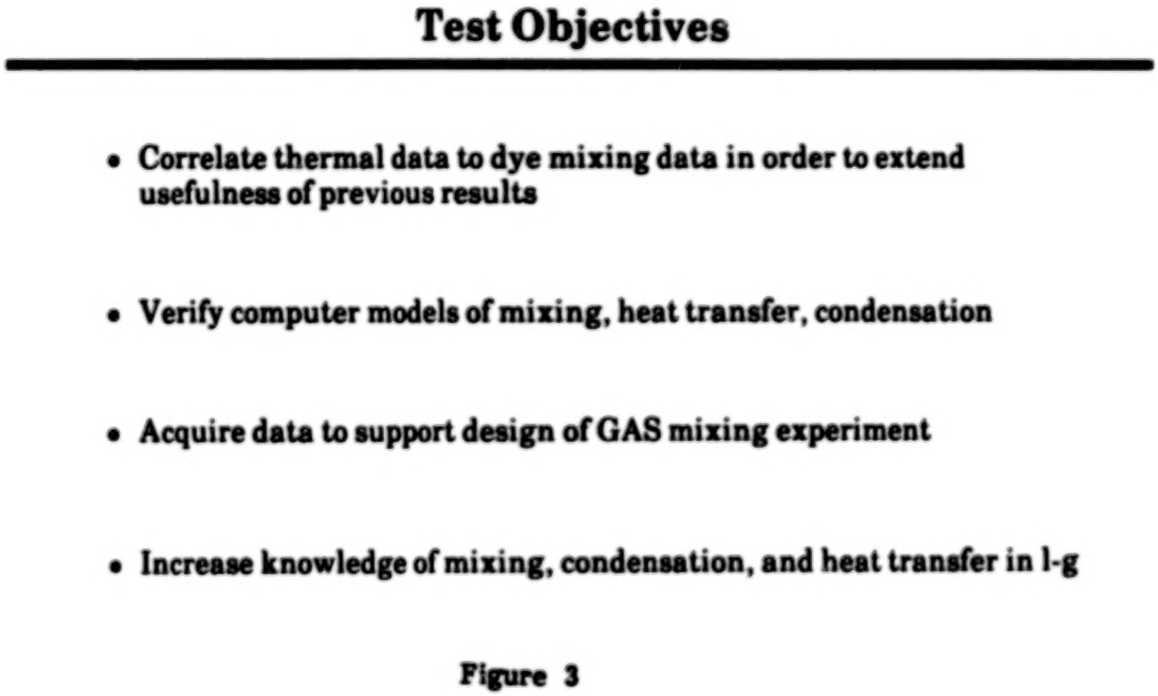

Test Objectives
• Correlate thermal data to dye mixing data in order to extend usefulness of previous results
• Verify computer models of mixing, heat transfer, condensation
• Acquire data to support design of GAS mixing experiment
• Increase knowledge of mixing, condensation, and heat transfer in l-g

Figure 3

TEST APPARATUS AND PROCEDURE

The test apparatus is a closed cylindrical tank with glass sides and stainless steel domes. The tank is insulated to minimize heat conduction through the tank walls. Within the tank is liquid and vapor Freon 11. This fluid was chosen because its boiling point at one atmosphere vapor pressure differs only slightly from room temperature. The tank is instrumented with thermocouples and pressure transducers. The mixer jet consists of a moveable tube that is fed by a positive displacement pump. The pump draws Freon from the bottom of the tank and circulates it through a heat exchanger to the mixer jet. In future experiments, the heat exchanger will be used to simulate a thermodynamic vent system heat exchanger. A circular heater coil is suspended just beneath the liquid surface.

Pressure Control Ground Experiment

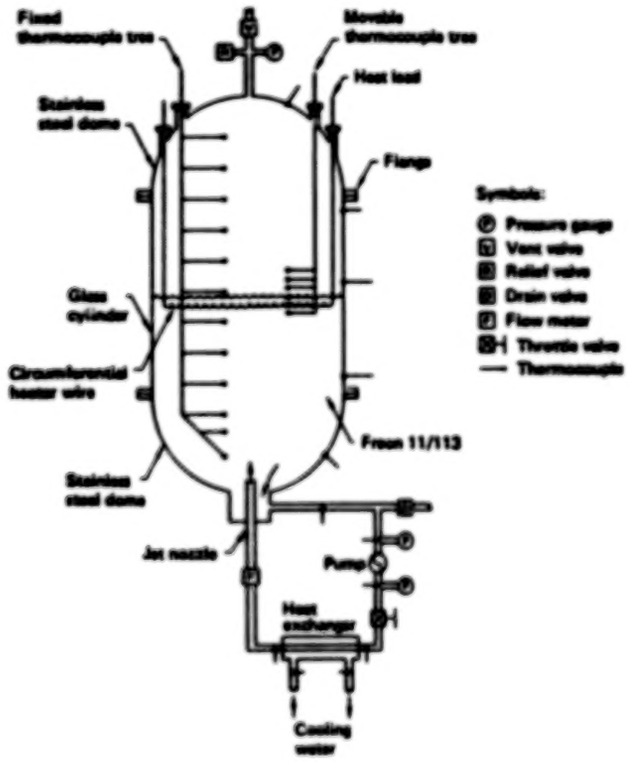
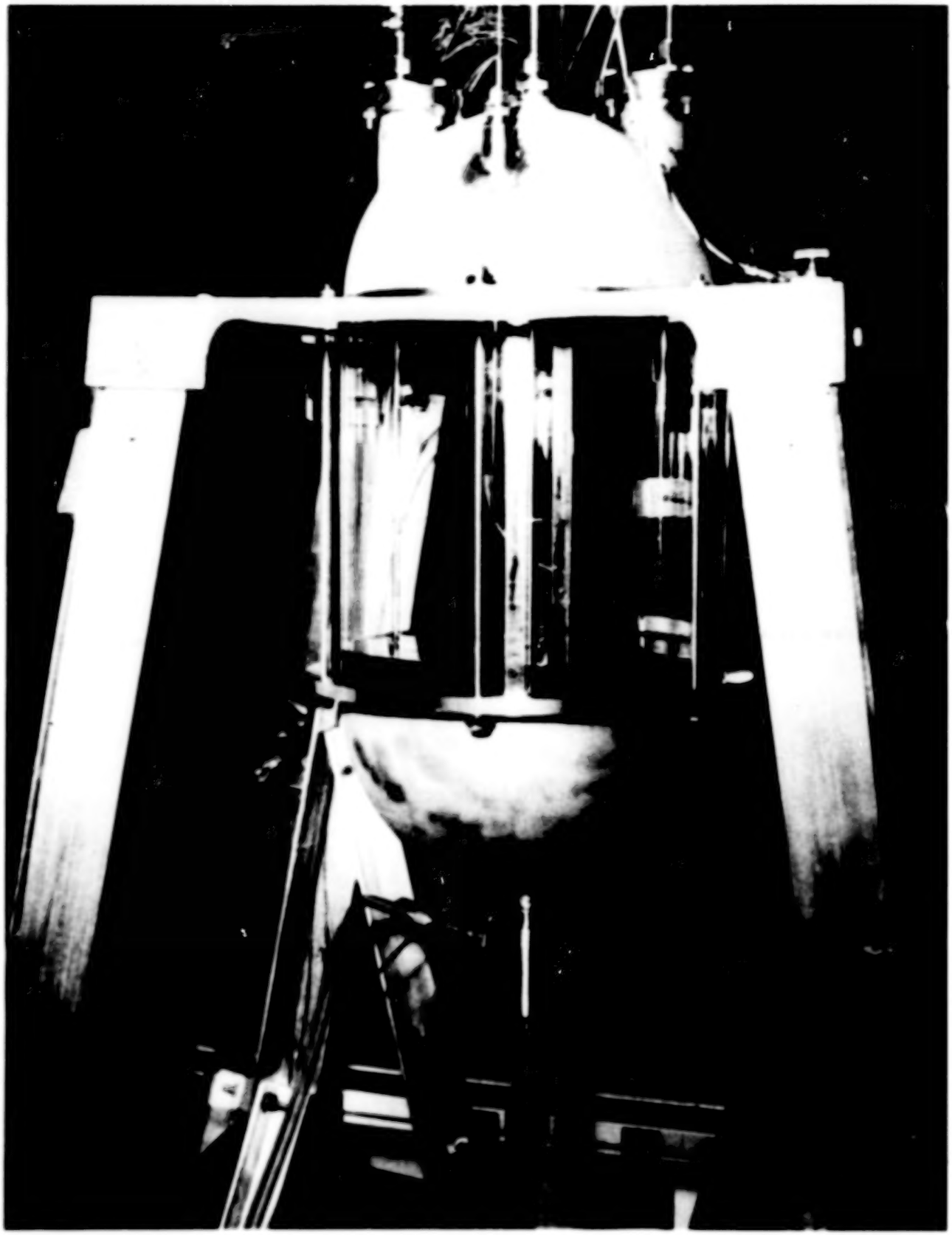


Figure 4

ORIGINAL PAGE IS
OF POOR QUALITY



The test was designed to be flexible, allowing us to gain as much information as possible from one apparatus. In the initial series of tests, however, we maintained many of the design variables constant. So that the results would more directly relate to changes in the mixer configurations, we kept the ullage fraction, heating rate, and total integrated heat input constant. The nozzle diameter, the flow rate, and the distance between the nozzle and the surface were varied.

The measured quantities are the ullage pressure and the vertical temperature profile in the tank. From this data, mixing times were calculated. The reference temperatures and pressures for these calculations were those that would correspond to the fluid in complete equilibrium (after heat has been added). The condensation rates were computed from the temperature and pressure data.

Test Parameters and Outputs

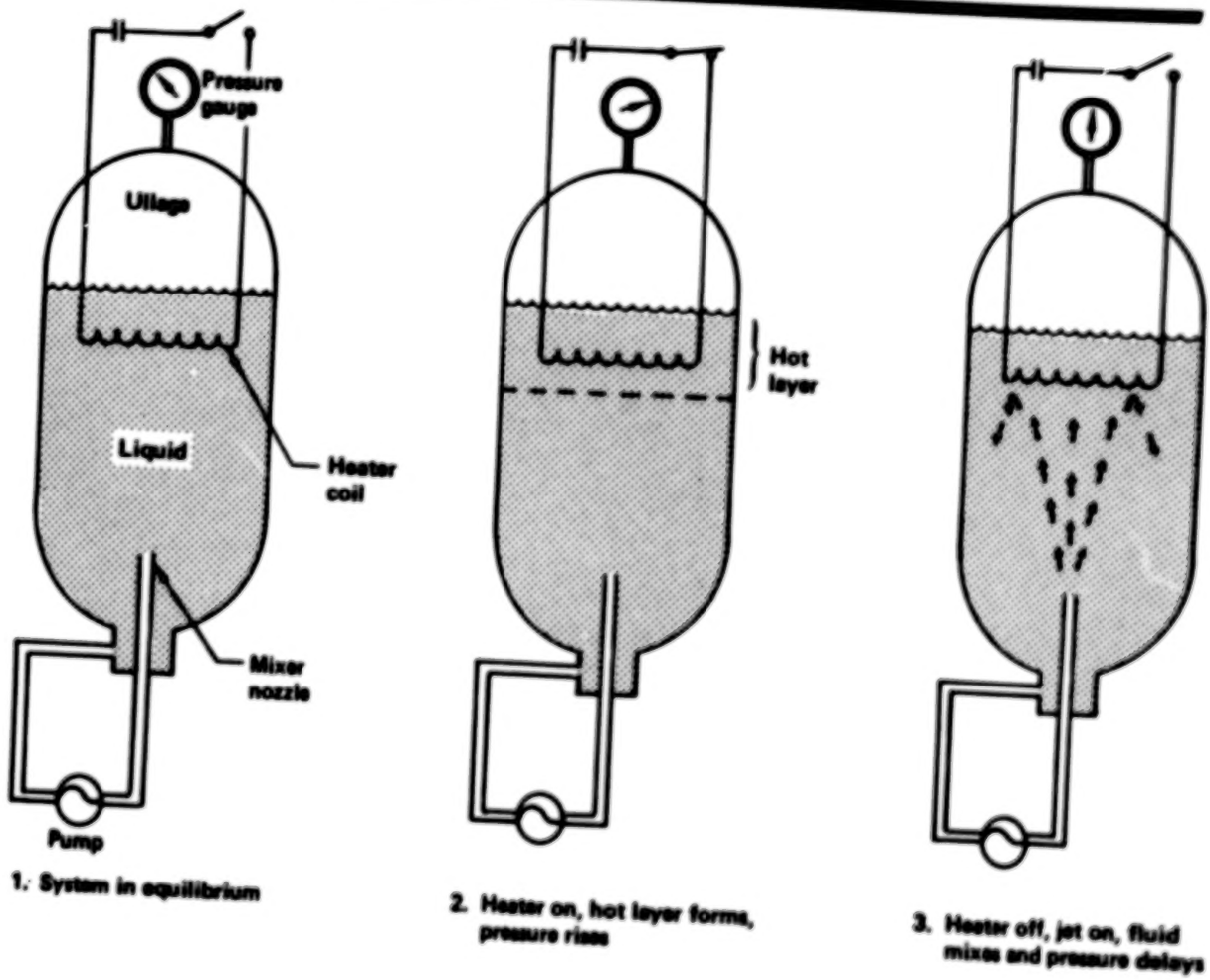
- Controlled variables
  - Heat input
  - Flow rate
  - Nozzle height (distance from nozzle to liquid-vapor interface)
  - Nozzle diameter
  - Ullage volume
- Measured variables
  - Ullage pressure
  - Temperatures in liquid and ullage
- Calculated quantities
  - Mixing time
  - Condensation rate

Figure 6

PROCEDURE

The Freon 11 is stratified by heating it just below the liquid surface. As the surface temperature rises, evaporation from the surface raises the pressure of the vapor. When a predetermined amount of energy has been added by the heater, the heater is shut off and the jet mixer turned on. The jet mixes the fluid, which lowers the surface temperature and causes the vapor to condense.

Test Sequence



1. System in equilibrium

2. Heater on, hot layer forms, pressure rises

3. Heater off, jet on, fluid mixes and pressure delays

Figure 7

RESULTS

Figure 8 shows a comparison of two experimental test runs and computer simulations of those runs. Both test cases had the nozzle near the bottom of the tank, but one was at a relatively low flow rate (.2 GPM), while the other was at a relatively high flow rate. The time is nondimensional with respect to the jet velocity and diameter at the nozzle and with respect to the tank diameter. The vertical axis is the ratio of the ullage pressure to the pressure corresponding to complete mixing.

While the two computer simulations and the high-flow-rate test case nearly collapse onto a single line, the low-flow-rate test data is markedly different. This is due to buoyancy effects, which were not included in the computer simulations and which become more apparent at low flow rates. At low-flow-rates, the jet does not have sufficient energy to overcome the buoyancy of the warm layer, so the surface temperature and hence the ullage pressure remain fairly constant. Notice that when the jet does break through the hot layer at time = 16, the pressure collapse rate is very nearly the same as in the other cases.

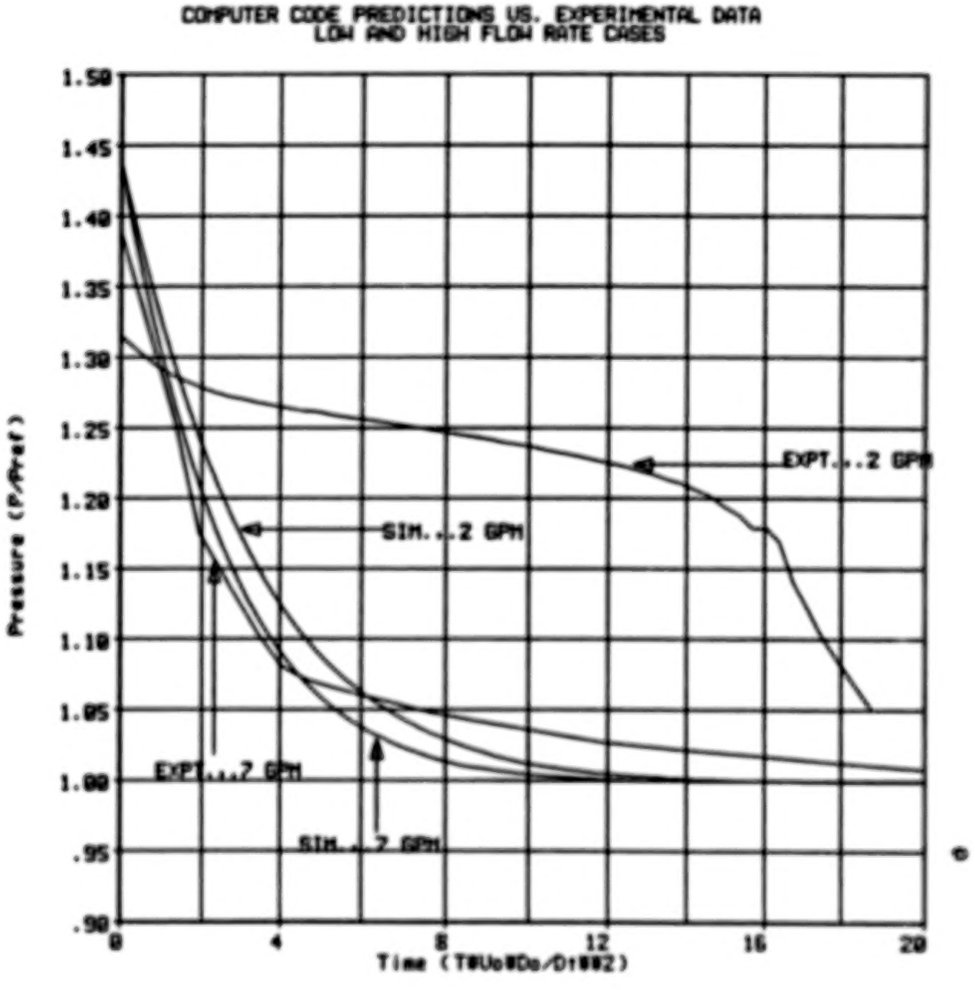


Figure 8

Figure 9 shows the correlation of the test data with a buoyancy parameter. The mixing time (surface temperature within 5% of the bulk temperature) is proportional to the Grashoff number, which is a measure of the strength of the buoyancy forces, and inversely proportional to the square of the jet Reynold's number, which is related to the energy of the mixer jet. For a low-gravity case, this parameter is small, and the mixing times would be shorter than our 1-g data indicates.

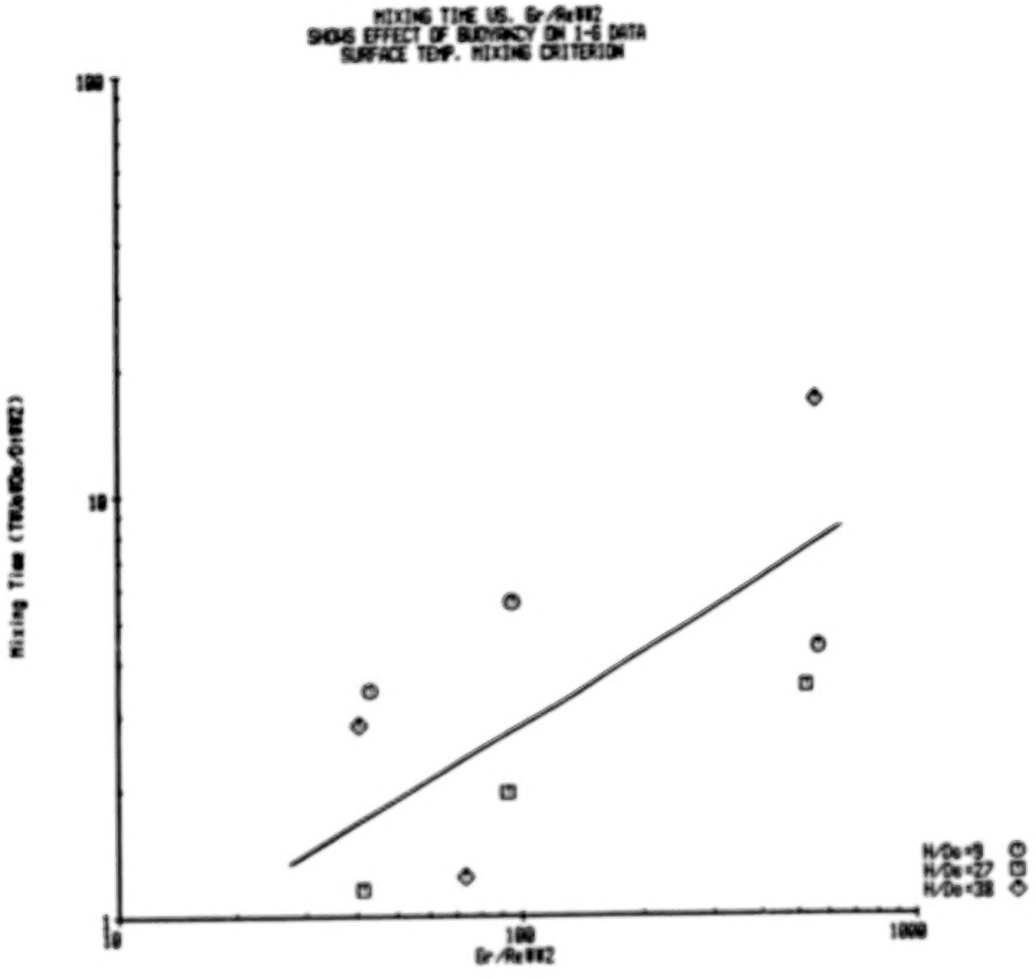


Figure 9

Mixing times can be defined in several different ways. The choice of which to use depends on the physical phenomena of principal concern. In Figure 10, we have defined the mixing time as the time for the surface temperature to fall to within 5% of the bulk liquid temperature. This definition gives a measure of the time required for the jet to sweep away the hot layer of fluid and replace it with cool liquid. Mixing times defined by ullage pressure collapse are nearly equal to this, since vapor pressure is related to the liquid surface temperature.

These data were compared to 1-g dye-mixing data obtained by Aydelott and to the General Dynamics acid-base neutralization data. Even though these sets of data comprise mixing times determined by visual observation of the complete dispersion of dye or acid neutralizer, they do indicate mixing times that are similar to the thermal mixing times for the surface layer. It is not clear, however, if this indicates a consistent correspondence between these two phenomena. Notice that for the thermal data, mixing time is less when the nozzle is farther away from the liquid surface (large H/D). The liquid jet from a nozzle near the surface apparently entrains warm liquid and recirculates it through the top liquid layer, thus mixing less of the cool liquid from lower in the tank.

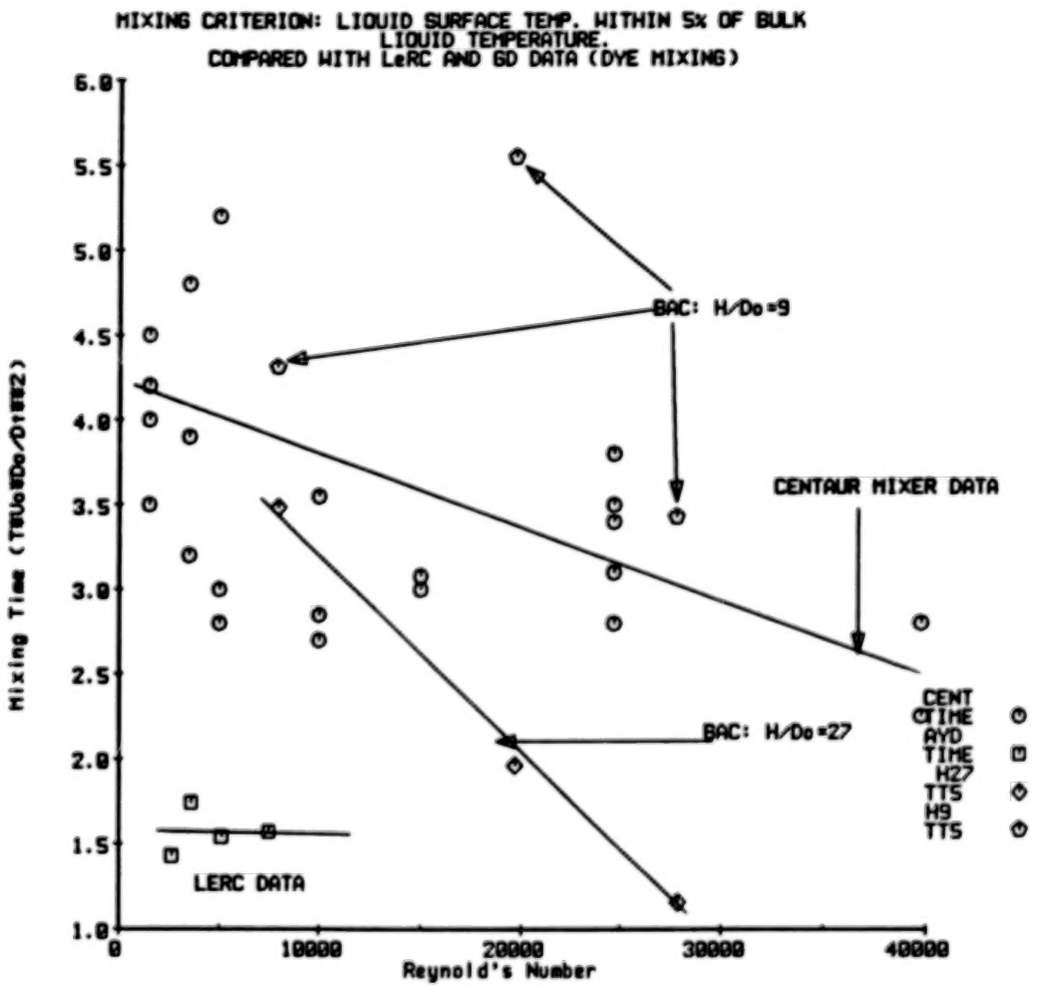


Figure 10

The thermal data in Figure 11 were derived using another definition of mixing time. In this case, it is defined as the time for all liquid temperatures to be within 1% of each other. This is a measure of the time required for complete mixing of the entire fluid. These data indicate mixing times an order of magnitude larger than those obtained in the dye and acid-base mixing experiments.

A possible explanation for the discrepancy is as follows. When the nozzle is close to the surface, circulation patterns may be established that prevent the liquid near the bottom of the tank from mixing with the hot top layer. When the nozzle is near the bottom of the tank (H/D = 27), and the jet Reynold's number is large, the mixing times begin to approach the LeRC and Centaur results. With a high enough flow rate, it is conceivable that buoyancy effects would be overwhelmed, and the thermal data would correlate with the dye dispersion data, which is not affected by buoyancy.

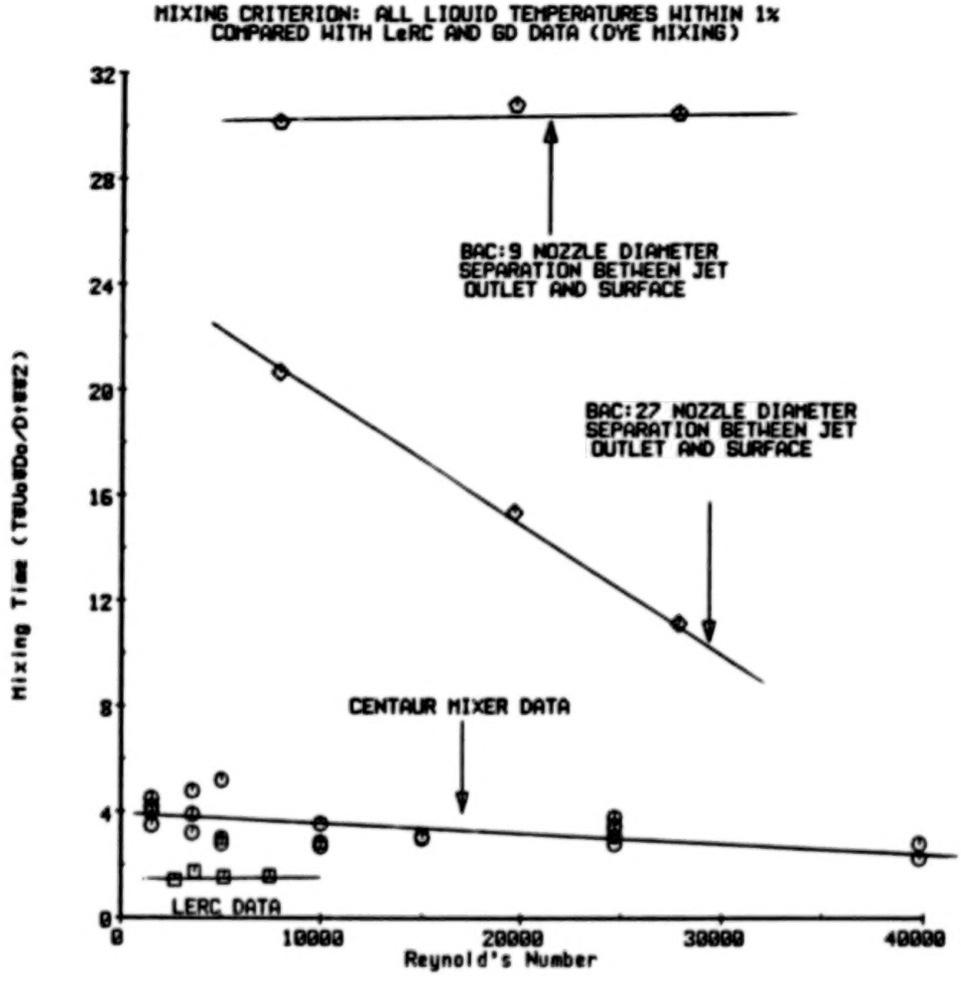


Figure 11

Figure 12 is another comparison between the thermal data and the data based on visual observation of dyed liquid. Poth injected dye on top of the water and then plotted the downward motion of the dye as a function of time after the mixer was turned on. Zhot is the height of the bottom of the dye layer, and Znoz is the height of the jet nozzle (both referenced to the bottom of the tank).

For the thermal experiments, we defined Zhot and Znoz in a similar fashion, but with Zhot as the height of the bottom of the stratified layer of fluid. When the layer was displaced downward by the mixer, its progress was revealed by the sudden increase in temperature at successive thermocouples.

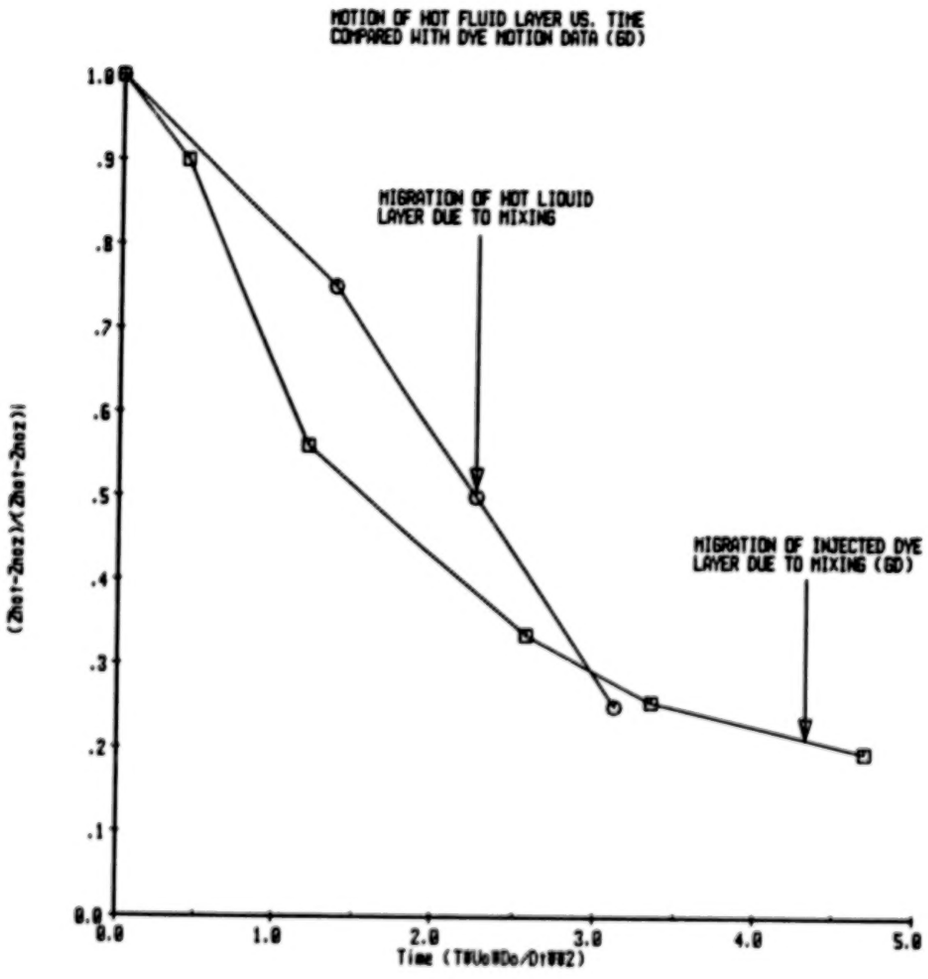


Figure 12

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PLANNED SPACE EXPERIMENT

The space experiment depicted in Figure 13 would operate similarly to the previously described ground experiment. The fluid will be Freon 113 rather than Freon 11, which would be chemically incompatible with the plexiglass tank. Electric heaters will locally heat the Freon to raise the tank pressure at the beginning of each test. A jet mixer will cool the heated zone while a digital data system records the tank temperature profile and the pressure collapse rate. A screened-channel liquid acquisition device will ensure that the pump draws liquid-free vapor.

The design for this experiment is nearly complete. Funding is being pursued, and our intent is to fly the experiment on the Space Shuttle as a Get-Away Special payload in two to three years.

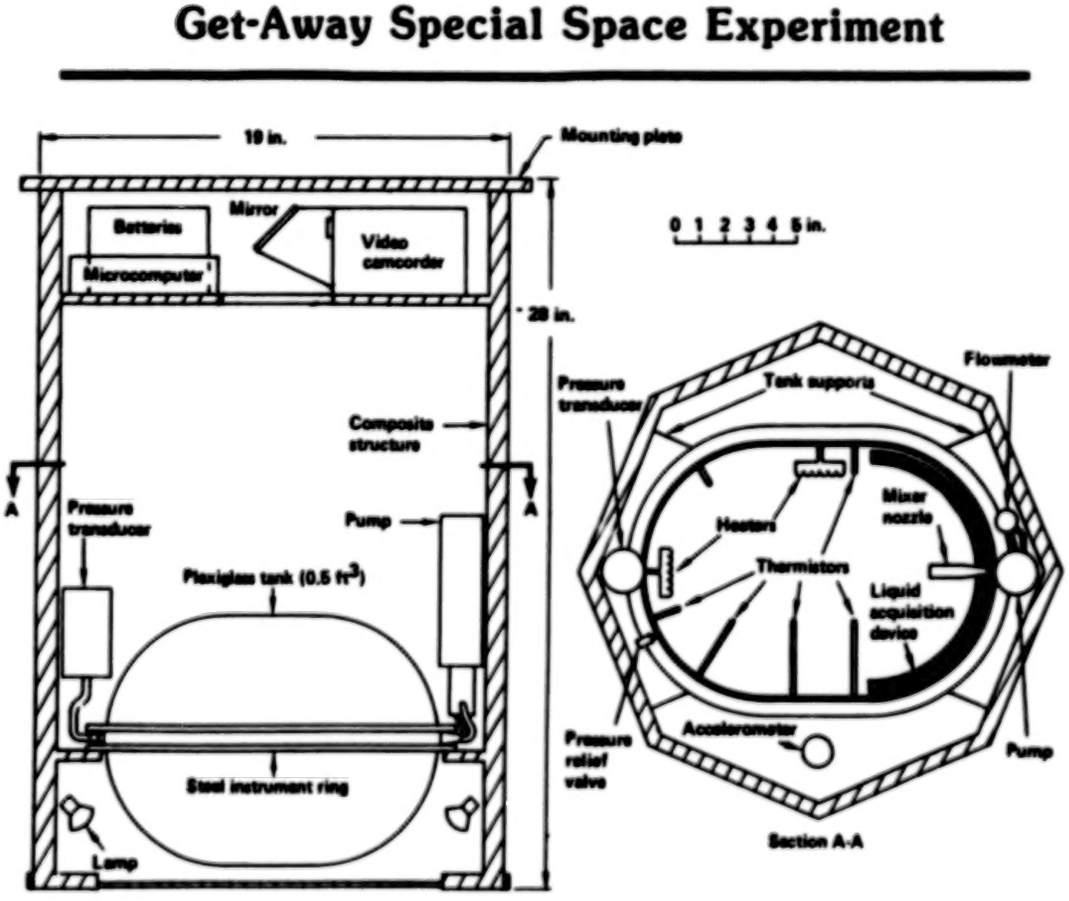

Figure 13

CONCLUSIONS

A few conclusions can be drawn from these initial results. Most notably, nondimensional pressure collapse times in our thermal mixing experiment are similar to the nondimensional mixing times obtained in 1-g and low-g dye mixing experiments. The time required to achieve complete thermal equilibrium in the liquid, however, is an order of magnitude longer.

A simple computer program shows good agreement with experiment data when buoyancy effects are small (that is, when the mixer flow rates are high).

With low flow rates, however, buoyancy effects significantly reduce the thermal mixing rates. Experiments in microgravity are necessary to obtain data spanning the full range of potential mixer operating conditions.

Conclusions

- Simple computer program can predict pressure collapse rates well, except when buoyancy is dominant (high Gr/Re^2)
- Dimensionless mixing times based on thermal equilibrium throughout liquid are much larger than those from previous studies based on the dispersion of dyes
- Dimensionless mixing times based on surface temperature (destratification) are similar to dye and acid-base data
- In 1-g tests, strong buoyancy effect makes measured mixing times conservative (higher) compared to expected low-g values
- Although 1-g data is useful for determining general trends, low-g thermal data is still necessary

Figure 14

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CRYOGENIC FLUID MANAGEMENT FLIGHT EXPERIMENT (CFMFE)

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Since its foundation, NASA has excelled in the study and development of microgravity fluid management technology. With the advent of space-based vehicles and systems, the use of and the ability to efficiently manage subcritical cryogens in the space environment has become necessary to our growing space program. The NASA Lewis Research Center is responsible for the planning and execution of a program which will provide advanced in-space cryogenic fluid management technology. A number of future space missions have been identified that will require or could benefit from this technology. These technology needs have been prioritized and the Cryogenic Fluid Management Flight Experiment (CFMFE) is being designed to provide the experimental data necessary for the technological development effort.

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SPACE EXPERIMENTATION REQUIRED

For over twenty years NASA Lewis Research Center has been conducting ground-based testing to characterize microgravity fluid management behavior. Many papers resulting from this work, as well as from contractor studies, have been written describing state-of-the-art cryogenic fluid management as well as the future needs of the space program. Because of the strong influence of gravitational fields on the thermophysical processes associated with the technology and the limitations of ground-based testing, in-space experiments are required.

IN-SPACE EXPERIMENTATION DRIVERS

- Fluid dynamic/heat transfer processes are strongly dependent on gravitational environment
- Most controlling processes cannot be adequately simulated in normal gravity testing
- Most feasibile ground-based testing has been completed
- Low gravity testing in drop towers/aircraft has been limited to small tanks and short test durations

IN-SPACE EXPERIMENTS ARE REQUIRED TO CHARACTERIZE GOVERNING THERMOPHYSICAL PROCESSES IN LARGE FLIGHT SYSTEMS

Table 1

Recognizing the need to go to space to properly characterize the processes of cryogenic fluid management, the approach shown in Table 2 was developed. NASA LeRC has been developing analytical models to characterize a complete cryogenic fluid management system. The three CFMFE missions will provide the parametric data needed to verify these models which will become design tools for future cryogenic systems.

CFMFE APPROACH

Design, build, and carry into space a reusable test bed to provide the technology required to manage subcritical cryogens in space.

- Conduct experiments in space to verify low-g fluid and thermal analytical models
- Use verified models to establish design criteria for subcritical cryogenic systems in space
- Use liquid hydrogen as test fluid
- Design for seven Shuttle flights (current mission planning for three flights)
- Utilize available expertise at LeRC, MSFC, JSC, KSC, ARC, JPL

Table 2

CFMFE Description

The preliminary design and mission planning for three flights of the CFMFE have been developed by Martin Marietta Denver Aerospace under contract to LeRC. The CFMFE is a Shuttle-attached, reusable test bed which will have a quarter payload bay allocation. It will be carried on a standard MDM pallet which interfaces with the Shuttle systems. The CFMFE (shown in Figure 1) is comprised of five major elements: 1) a cryogenic liquid storage and supply system, 2) a fluid transfer line and receiver tank, 3) a high pressure gas pressurization system, 4) the supporting structure including a subpallet which is attached to the MDM pallet, and 5) a facility control and data acquisition system.

Liquid hydrogen has been selected as the CFMFE experimental fluid because of its prominent planned use for future NASA and DOD missions. In addition, liquid hydrogen presents challenging in-space fluid management requirements due to its low temperature, density and suface tension properties. Obtaining low-g storage, supply, and transfer data for hydrogen will, therefore, have general applicability to other cryogenic fluids, with the exception of liquid helium.

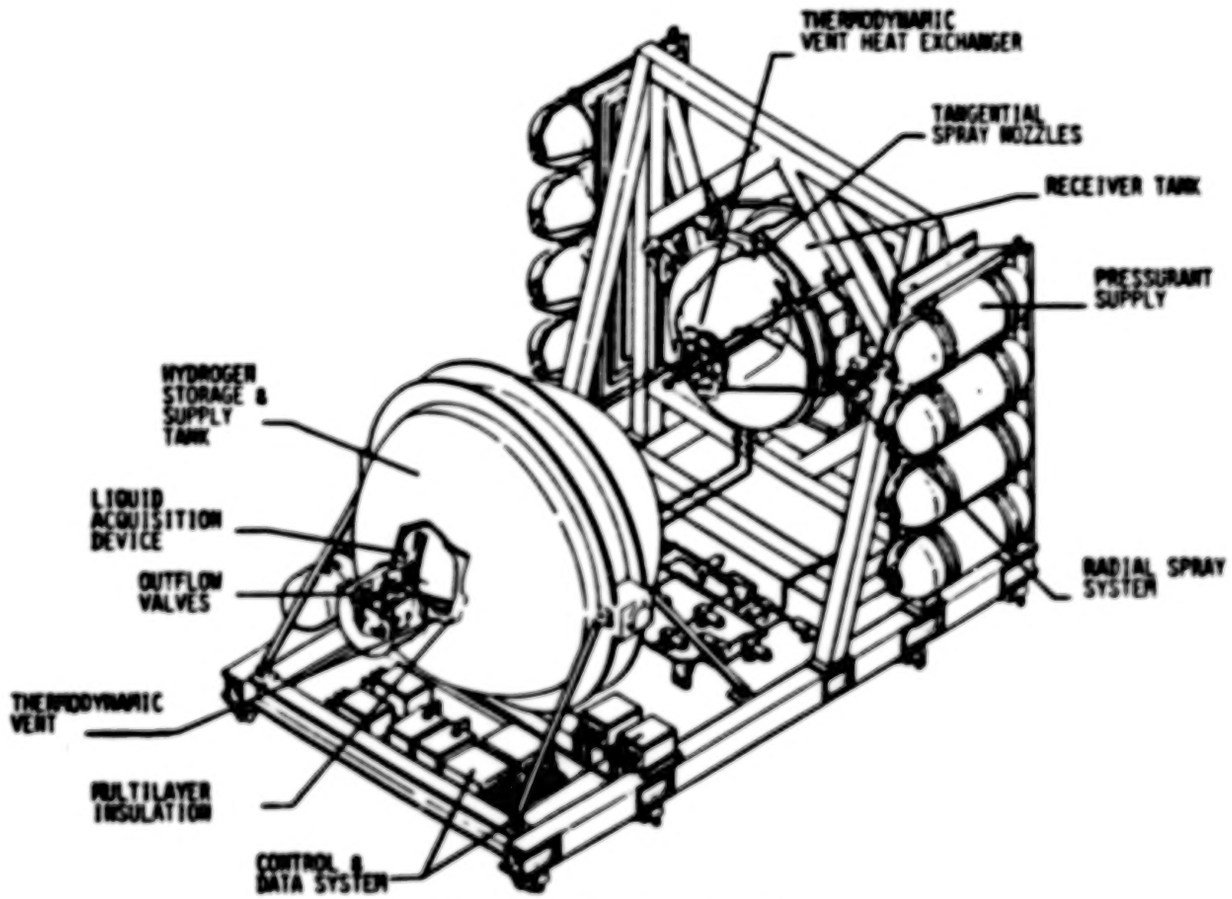

Figure 1 CFMFE Subpallet

The cryogenic fluid management technologies selected for investigation on the CFMFE are listed in Table 3. Each technical objective has been assigned a technical priority for each of the three missions. The priorities were assigned on the basis of their impact on future NASA and DOD missions and on the necessity to conduct experimentation in the space environment. These priorities will be used to determine the amount of dedicated instrumentation required to achieve each objective and the amount of parametric variation required.

CFMFE EXPERIMENTAL OBJECTIVES	TECHNICAL PRIORITY BY MISSION		
	I	II	III
I. Liquid Storage			
A. Storage tank thermal performance characterization	2	2	2
B. Receiver tank thermal performance characterization	3	3	3
C. Pressure control via Thermodynamic Vent Systems	2	2	2
II. Liquid Supply			
A. Pressurization			
1. Gaseous helium	2	2	2
2. Autogenous (GH_2)	2	N/A	2
B. Acquisition/Expulsion			
1. Receiver tank direct liquid outflow with low-g settling	2	2	N/A
2. Total communication capillary Liquid Acquisition Device (LAD) performance	2	2	2
3. Partial communication capillary LAD (start basket) performance	N/A	N/A	2
III. Fluid Transfer			
A. Transfer line chilldown	2	2	2
B. Thermal conditioning of liquid outflow	2	2	2
C. Receiver tank			
1. Chilldown with spray	1	1	1
2. No-vent fill	1	1	1
3. Venting of noncondensible gas	2	N/A	N/A
4. No-vent refill	1	N/A	N/A
5. Start basket fill	N/A	N/A	2
D. Supply tank			
1. No-vent refill including LAD	1	N/A	N/A
2 . No-vent fill including LAD	N/A	1	2
E. Quantity gauging instrumentation	3	3	3

Table 3

The CFMFE design provides the development of on-orbit cryogenic fluid storage, supply, and transfer applicable to several fluids and a variety of space systems. Table 4 (shown below) lists some of the potential applications of this technology.

POTENTIAL APPLICATIONS

- o Earth-to-orbit transport and in-space storage of cryogenic liquids
- o On-orbit fueling of propulsive stages
- o Space Station subsystem fluid replenishment
- o Experiment and satellite fluid resupply
- o Resupply of space-based SDI reactants, coolants, and propellants

Table 4

Schedule

The CFMFE Master Schedule for the three missions currently being planned is shown in Figure 2 (below). The project is proceeding per this schedule; however, the actual launch dates may be affected by the new Shuttle manifest plan which is itself dependent on the actual data of the resumption of Shuttle operations.

CFMFE MASTER SCHEDULE

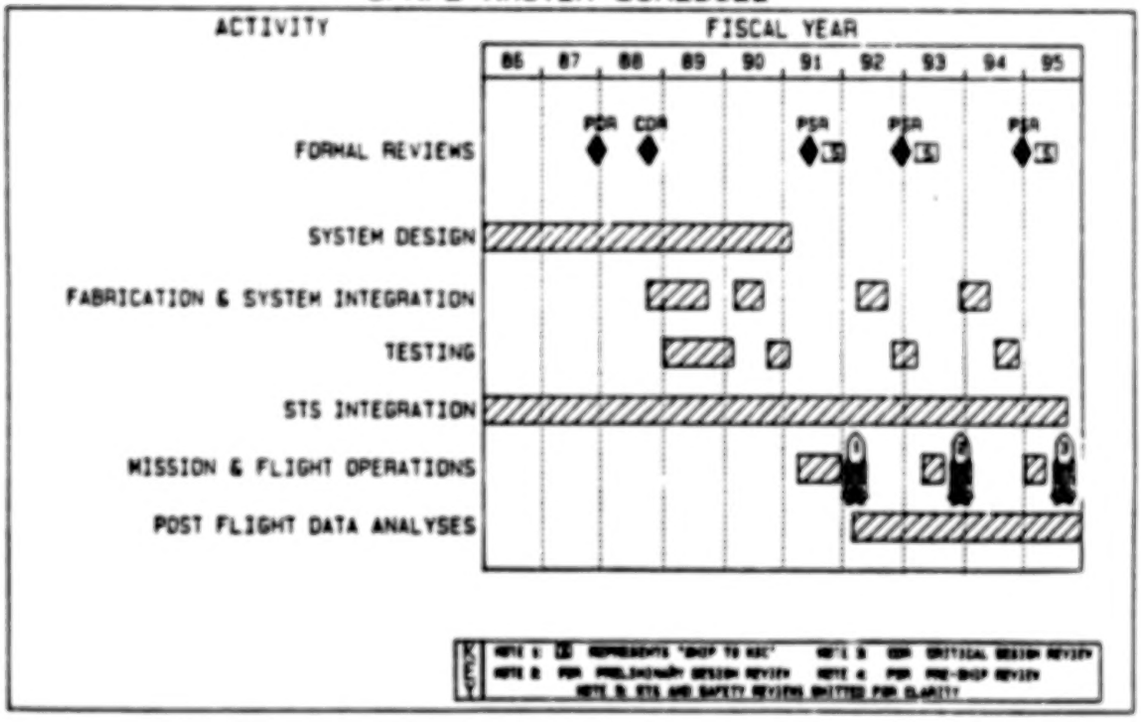

Figure 2

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SUPERFLUID HELIUM ON ORBIT TRANSFER (SHOOT)

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Greenbelt, Maryland

A number of space flight experiments and entire facilities require superfluid helium as a coolant. Among these are the Space Infrared Telescope Facility (SIRTF), the Large Deployable Reflector (LDR), the Advanced Xray Astrophysics Facility (AXAF), the Particle Astrophysics Magnet Facility (PAMF or Astromag), and perhaps even a future Hubble Space Telescope (HST) instrument. Because these systems are required to have long operational lifetimes, a means to replenish the liquid helium, which is exhausted in the cooling process, is required. The most efficient method of replenishment is to refill the helium dewars on orbit with superfluid helium (liquid helium below 2.17 Kelvin). To develop and prove the technology required for this liquid helium refill, a program of ground and flight testing was begun. The flight demonstration is baselined as a two flight program. The first, described in this paper, will prove the concepts involved at both the component and system level. The second flight will demonstrate active astronaut involvement and semi-automated operation. The current target date for the first launch is early 1991.

This paper describes the objectives of the program, some of the critical components developed for the flight, and the progress to date in their development.

A number of space facilities will require superfluid helium (SFHe), that is liquid helium below 2.17 Kelvin (K), to cool individual instruments or the entire facility. These facilities are required to have long lifetimes, and since the helium is gradually expended to provide cooling, it must be replenished. By far the most economical method would be to resupply the superfluid helium to the facility on orbit. The technology necessary to accomplish this is to be demonstrated by the SHOOT Flight Demonstration. Critical components must be designed, developed, and where feasible, tested on the ground. The complete system, including fluid acquisition devices which cannot be adequately tested on the ground, must then be tested on orbit. Diagnostic instrumentation, such as mass gauging instruments,flow meters, and perhaps liquid/vapor detectors will also be developed and demonstrated on this mission.

The SHOOT experiment as pictured here atop a Multi Purpose Experiment Support Structure (MPESS), consists of two 210 liter capacity liquid helium dewars with demountable cryostats and electronics for control and data acquisition. The entire assembly excluding MPESS and Hitchhiker avionics weighs 950 pounds. The dewars are designed to allow the removal of any critical component to allow easy changeout. To this end nearly all the components, including valves, plumbing, burst disks, couplings, wiring, and instrumentation are part of the removable cryostats. The dewars are linked by a vacuum jacketed transfer line, through which the superfluid helium may be pumped in either direction.

SUPERFLUID HELIUM ON ORBIT TRANSFER FLIGHT DEMONSTRATION

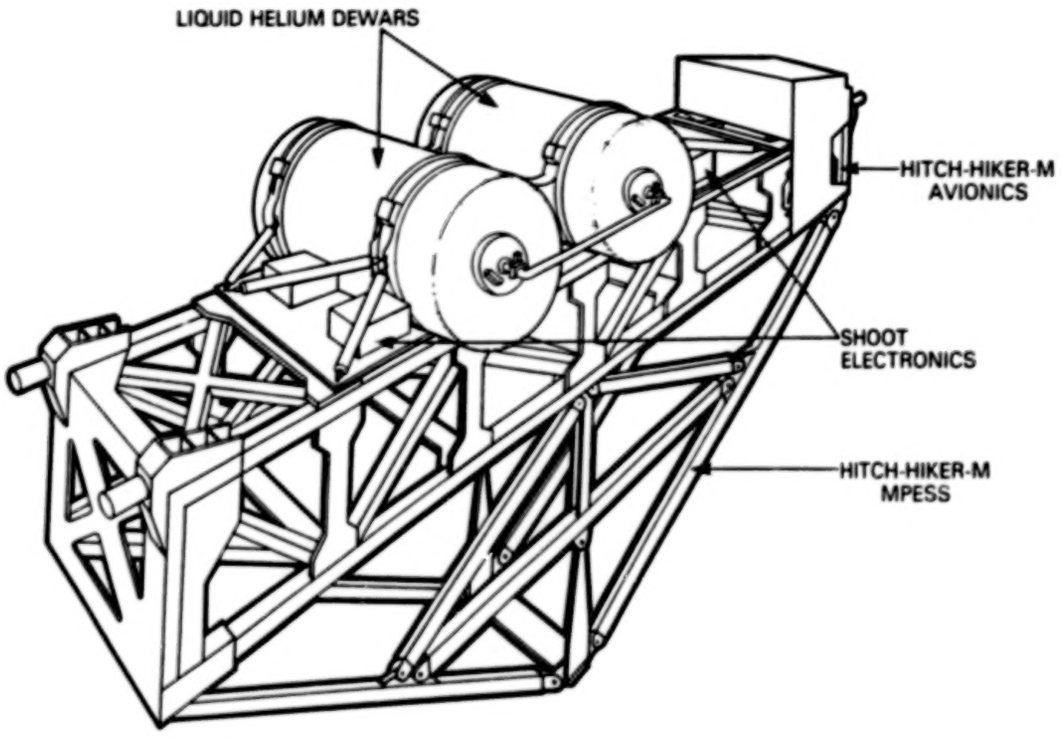

Figure 1

Figure 2 is a schematic of the dewars and cryostats emphasizing the valving and plumbing. The cryostats are identical to allow each to operate as the supply or the receiver dewar. This gives more time for experimentation allowing helium to be transferred back and forth between the two dewars. A typical transfer sequence goes as follows:

- Initial state: valves A,B,C,D,E closed, valves F,G,H open, transfer line warm

- Precool transfer line: open valves B(source), E(receiver), start pump

- Begin transfer: open valves C,D(receiver), D(source), close valve E(receiver), adjust pump for optimum flow

- Monitor transfer: perform mass gauging operation, flow checks and temperature checks

- Stop transfer: stop pump, close valves B,D(source), C,D(receiver), open valves E

SHOOT DEWAR & CRYOSTAT WITH TM PUMP

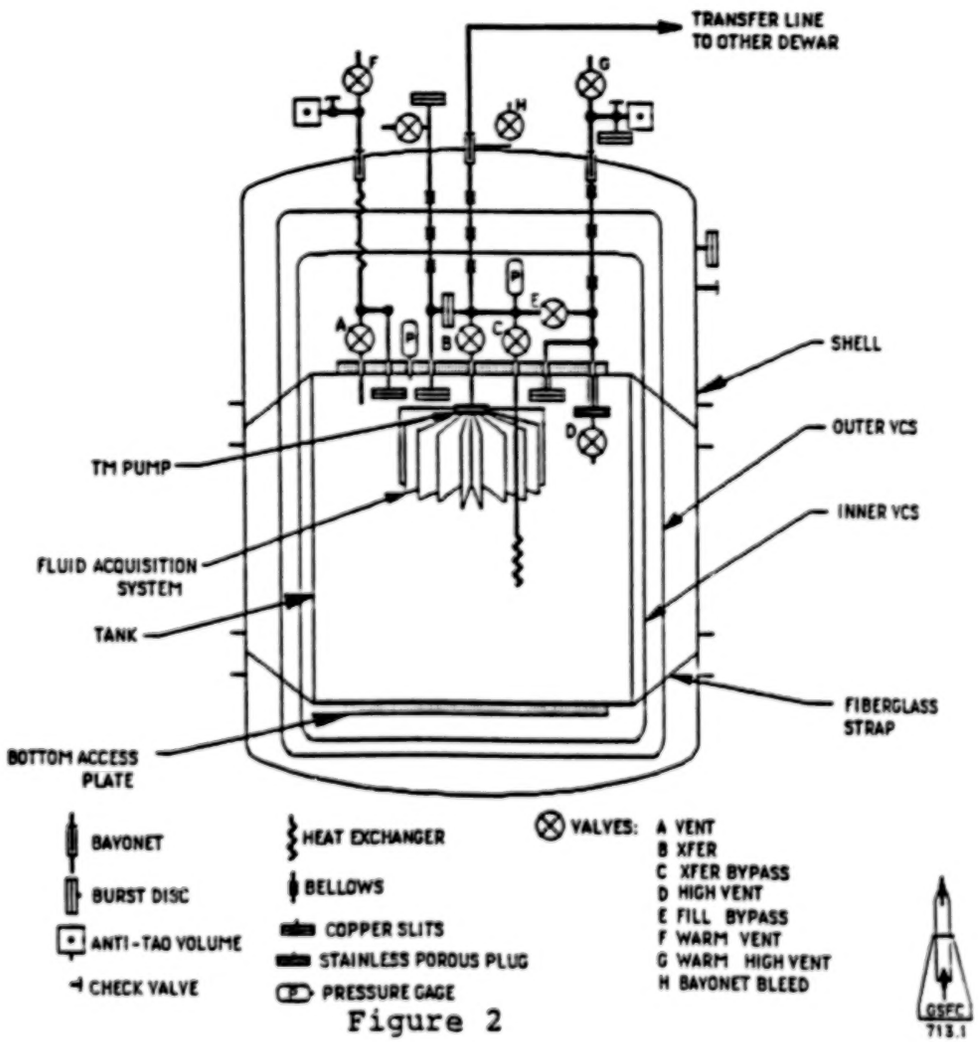

Figure 2

Containing liquid helium within the dewars in a low g environment requires a method to separate the liquid phase from the vapor phase. In previous superfluid helium space dewars this function was performed by a porous plug; a disk made of sintered metal powder with an interconnected array of pores of the order of a few microns in diameter. Phase separation is achieved utilizing the thermomechanical (TM) effect, a property unique to superfluid helium. Briefly, the effect is described as follows. SFHe may be modeled as two interpenetrating fluids, a "normal" fluid with a viscosity and the ability to transport heat (entropy), and a "super" component having zero viscosity and entropy. The relative densities of the two fluids are determined by the temperature; the lower the temperature the higher the proportion of super component. Referring to figure 3a, when container A is heated, the normal component moves from A to B carrying heat. Super component in B moves counter to the normal component to keep the relative densities of the two components and hence the temperatures of A and B nearly equal. This convective type motion of SFHe makes it a very good thermal conductor. When a constriction, such as a porous medium, is introduced between the two containers, the flow of the normal helium (and hence the heat) is impeded due to its viscosity, while the super component may still pass freely. The chemical potential difference between the hotter A and cooler B drives the super component into A as in Figure 3b. Net flow stops when the chemical potential due to the temperature difference is balanced by the hydrostatic potential due to the pressure head as in Figure 3c. This is the basis for the TM pump described later. Figure 3d indicates that if B were allowed to deplete, the porous plug would become a phase separator, with liquid boiling at its surface and the TM pressure overcoming the saturated vapor pressure to contain the liquid in A.

The pore size and total cross-sectional area is crucial to the proper operation of the porous plug. The pores must be small enough to restrict the flow of normal component, but at the same time be large enough to carry heat out of the dewar to the outer surface of the plug where evaporation of the helium, and hence the cooling, takes place. Furthermore, if the pores are too small for the heat load, the TM pressure will be large enough to drive the liquid back into the porous plug allowing only vapor through the pores, increasing the pressure drop and hence the temperature within the dewar. Reference 1 contains further details. The high vent porous plug on SHOOT downstream of Valve D is sized to accomodate 2 to 30 Watts of heat input to the dewar, typical values for the heat generated in the supply dewar during transfer. Valve D will be closed at other times to prevent SFHe from escaping through the rather large pores of this plug.

THERMOMECHANICAL EFFECT

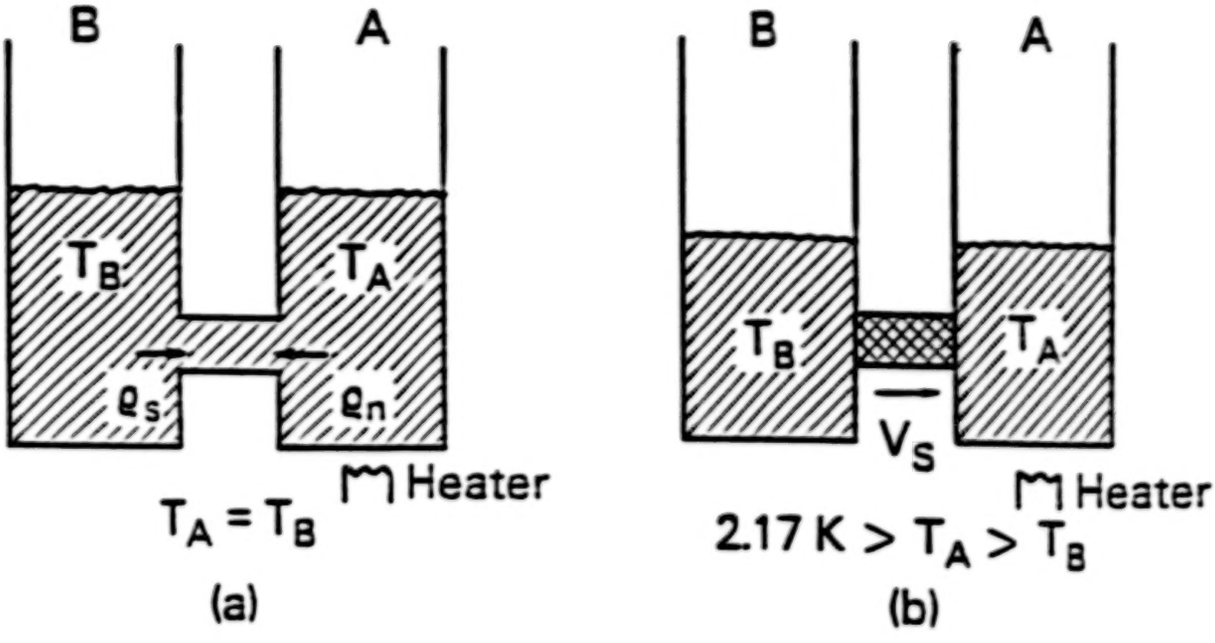

Figure 3

The previous method of phase separation works only with SFHe. With liquid above the superfluid transition temperature such as will occur during cooldown of a warm dewar, another method of phase separation must be devised. We are presently developing a thermodynamic phase separator which will also work with SFHe at low flow rates. The principle is to force the escaping liquid off the liquid/vapor coexistence curve by limiting flow and heating. To be efficient, all the heat must be obtained from the remaining liquid within the dewar. The phase separator must provide adequate heat and fluid flow to cool the remaining liquid in a reasonable time and at the same time, not compromise the fluid retaining capability for SFHe to a degree such that a low level adverse acceleration would overcome the TM pressure. Further details are given in reference 2. The conditions require small, relatively uniform flow paths surrounded by high thermal conductivity material. We are trying two geometries to accomplish this. The first is shown in Figure 4, consisting of a number of approximately 5 micron wide slits in parallel fabricated from high conductivity 99.999% pure copper. The second technique being used by Alabama Cryogenic Engineering is to make a number of parallel pores of approximately 1 to 1.5 micron diameter in OFHC copper.

LIQUID HELIUM (He I) PHASE SEPARATOR
COPPER SLIT DESIGN

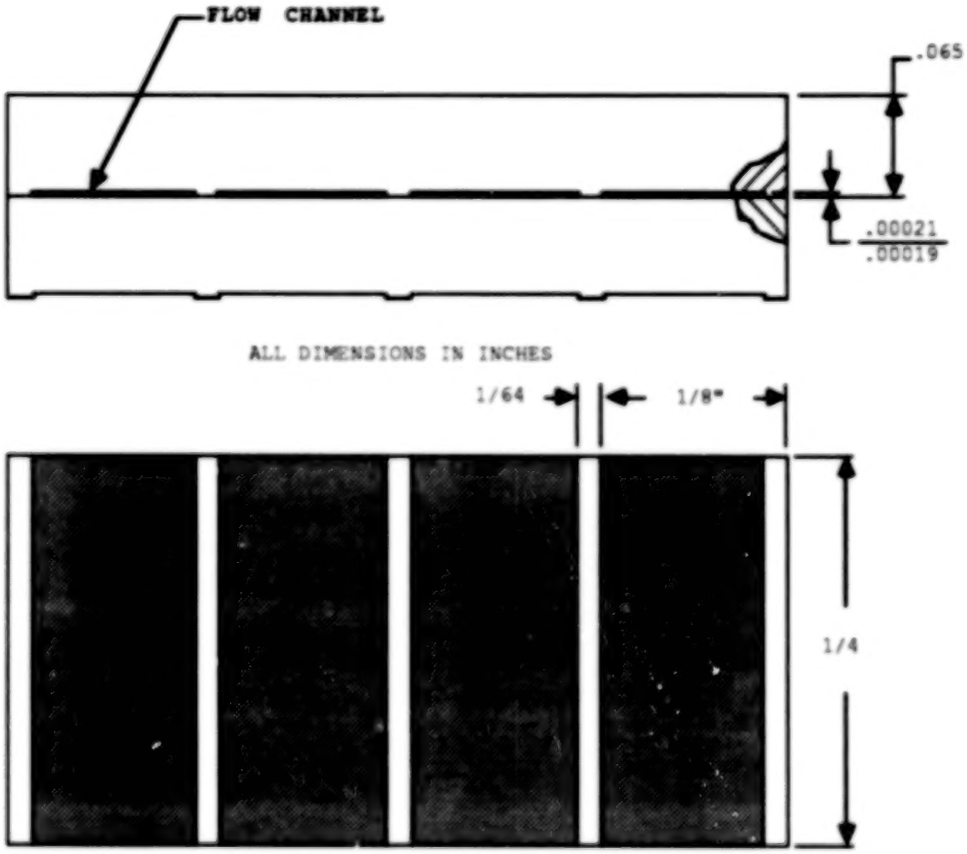

Figure 4

The TM effect as previously described has been known for a few decades. It has also been used on a laboratory scale as a pump to move small amounts of SFHe. We have been developing a TM pump for use on SHOOT capable of transfer rates in excess of 500 liters per hour. As first steps in the development of this pump we have made and tested two smaller versions; one using a porous plug of the type used in the Infrared Astronomy Satellite (IRAS), and the second using a porous plug of much smaller pore size. In both cases the plugs were much smaller in diameter (by factors of 6 and 5 respectively) than the SHOOT TM pump will require. The main limitation of our ground based system has been the relatively low pumping speed of our helium bath mechanical pumps when compared to the flight vent system. As the mechanical pump system is upgraded, the size of TM pump and hence the maximum SFHe transfer rate will be increased to near that expected in flight.

Figure 5 is a schematic of the SHOOT TM pump, a relatively simple device using a porous plug with nominal 1 micron diameter pores, a woven wire heater on the downstream side and germanium resistance thermometers (GRT'S) on both sides to monitor performance.

TM PUMP SCHEMATIC

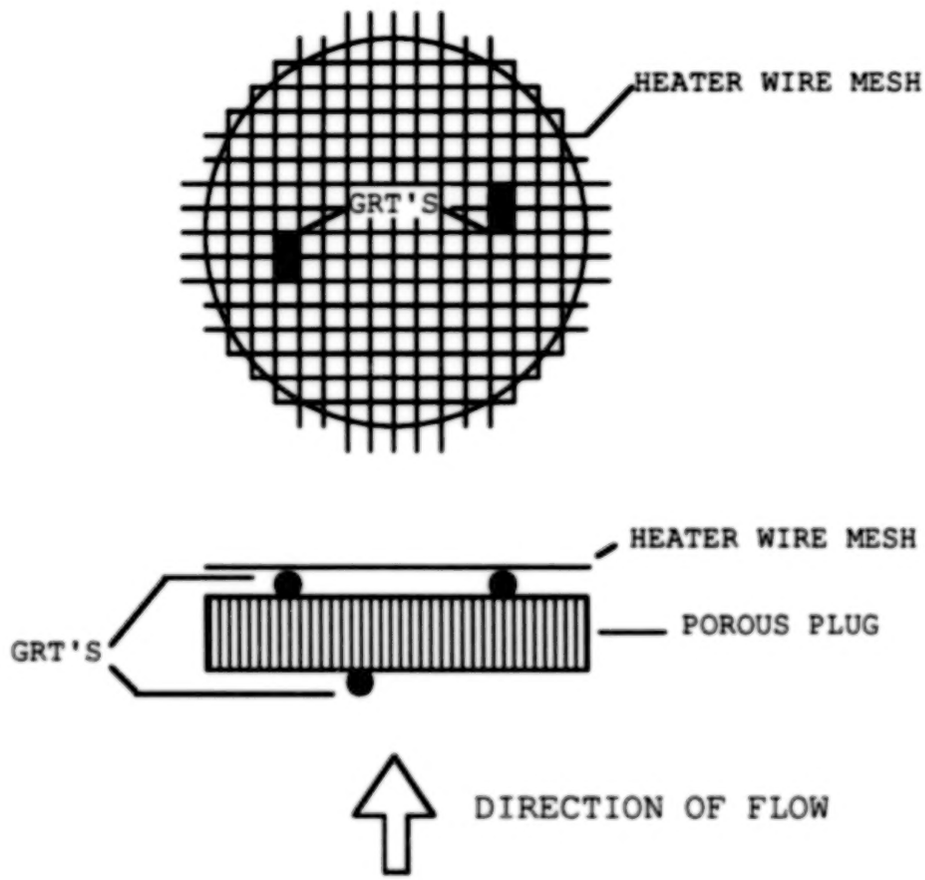

Figure 5

Laboratory test results, plotted as efficiency versus transfer rate, are shown in Figure 6. Efficiency is defined here as the mass transferred divided by the mass removed from the source dewar. The amount transferred is reduced by the mass that would be lost in order to pump the receiver back down to the temperature of the SFHe in the source dewar. All values are approximately those of steady state, i.e., start up transients were excluded from the data.

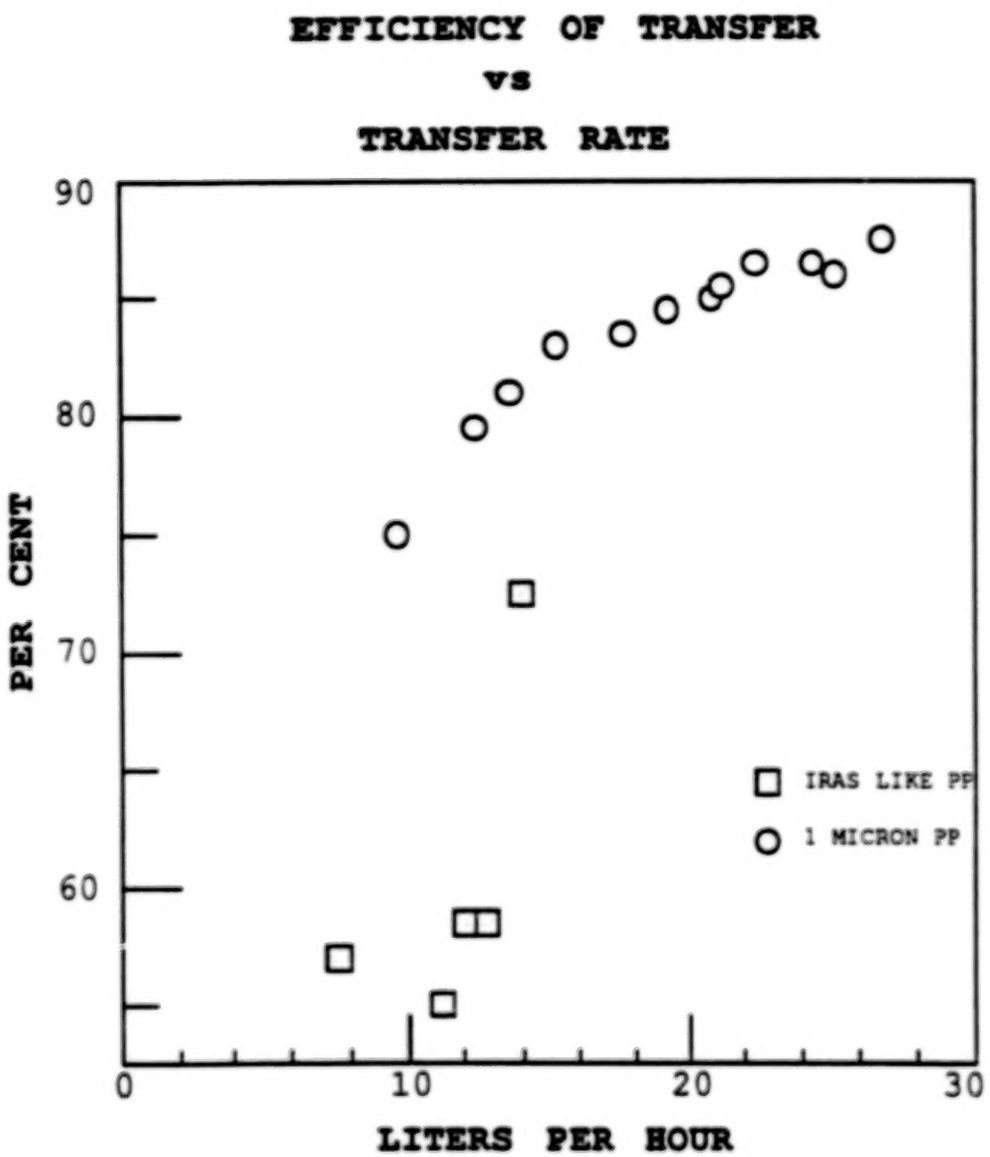

Figure 6

The majority of the losses in these measurements was due to the parasitic heat leak into the SFHe from the transfer line. In the first case the heat leak was approximately 3 Watts and in the second 2 Watts. The heat leaks resulted from bayonet couplings in the first case and lack of Multilayer Insulation (MLI) in the second. While these heat loads would be acceptible for a full up flight system (the goal is 3 Watts for SHOOT), they are comparitively large when the transfer rate is small as in these subscale experiments. The next ground test set up will use a much better insulated transfer line with a state-of-the-art bayonet coupling as described in the next section. Figure 7 indicates the performance of the lab TM pumps when the transfer line parasitic heat leak is scaled back to Ø.15 W. The ideal efficiency of the TM pump is strongly dependent on the source dewar temperature, however for the expected range of temperatures the ideal losses are calculated to be between 1.5 and 4 %.

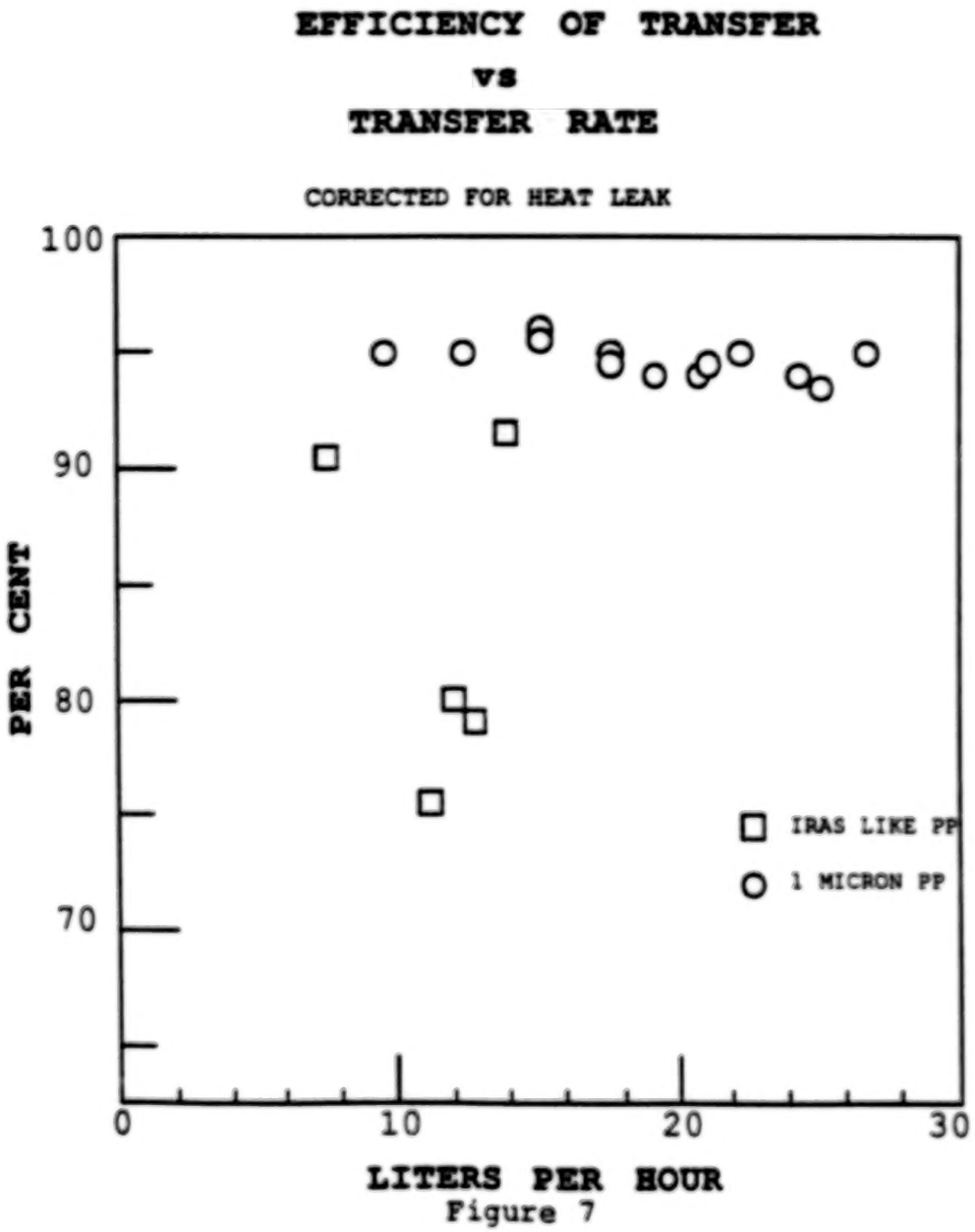

Figure 7

One of the largest potential parasitic heat leaks is due to the transfer line coupler. Prior to 1986 the lowest heat leak for a such a coupler was about 1.3 W, due mostly to conduction down the bayonet walls and leaks past rudimentary nose seals. Cryolab, Inc. designed and developed a high performance bayonet coupler for potential use in SHOOT. The results of tests using SFHe indicated a remarkably low 0.25 W heat leak into the nominal 0.5 inch diameter line. (See Reference 3.) Figure 8 shows the design of the laboratory model produced by Cryolab. Many of these design features may be incorporated into the flight couplings to be used in SHOOT.

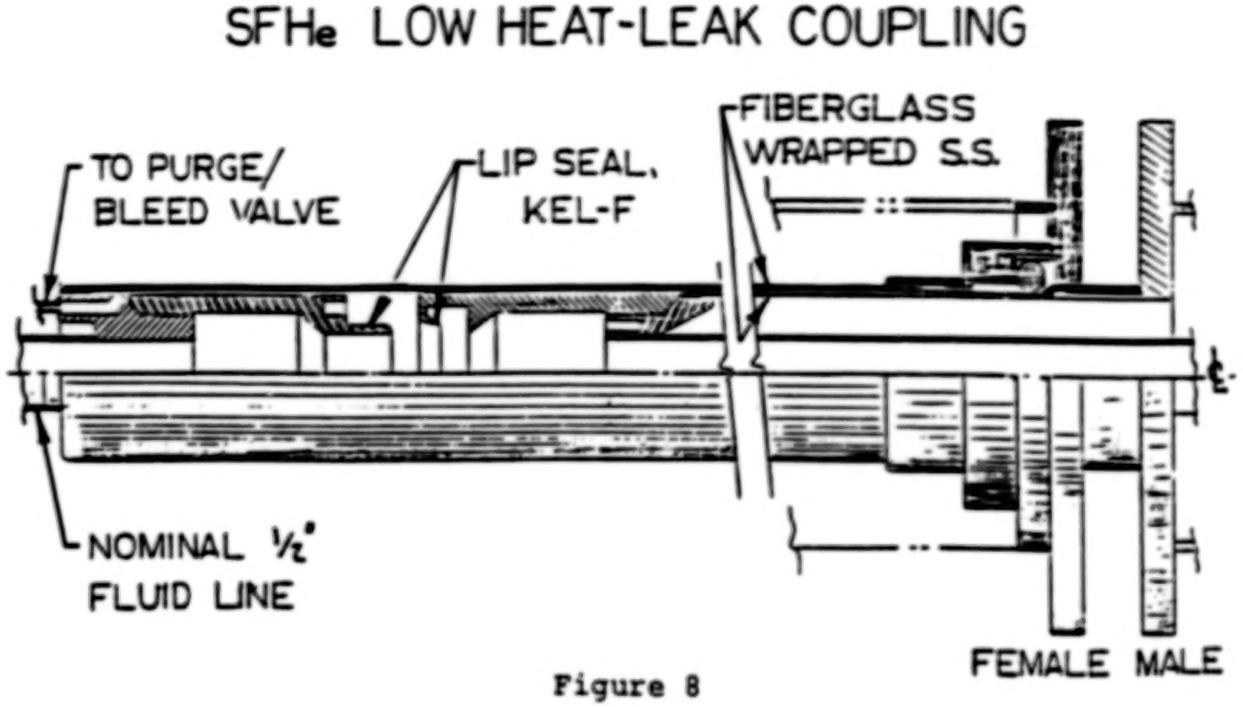

Figure 8

One component that requires a long term micro-g environment to be fully tested is the fluid acquisition system that provides SFHe to the pump inlet at a rate equal to the desired transfer rate. The present concept for the fluid acquisition system uses two parts: a sponge in intimate contact with the pump inlet, and either a screened channel or capillary system along the dewar walls providing SFHe to the sponge. The screened channel system uses a differential pressure to move liquid into the channels with the fine mesh screen preventing gas from entering the channel due to surface tension. For most liquids a differential pressure can be easily maintained, however, due to the high thermal conductivity of SFHe a temperature differential and hence a pressure exceeding the saturated vapor pressure will be difficult to accomplish. The only hope for this technique is the fact that the fine mesh of the screen will limit the heat flow by limiting the flow of normal component. As an alterate, a capillary action device such as closely spaced fins or wires along the dewar walls may be used. Laboratory tests of a subscale model of a screened channel device prepared by Martin Marietta Corporation are being readied at Goddard to aid in the device selection.

OTHER COMPONENTS

- Cryogenic valves - stepper motor driven SFHe leak tight valves able to operate at SFHe temperature

- Burst disks - relief devices to prevent crogen tank burst, precisely calibrated to burst at 22 psid at liquid helium temperatures

- Electrical feedthroughs - SFHe leak tight multi-pin electrical feedthroughs for use at liquid helium temperature

- Mass gauging instrumentation - 0.00005 K precision, 0.001 K accuracy GRT's and readout system and heaters for heat capacity mass determination

- Flow meter - possible use of venturi type or heat transport type flow meter in transfer line

- Other instrumentation - diagnostic GRT's and heaters, pressure transducers, and possible liquid/vapor phase detectors

SUMMARY

A need has arisen for the replenishment of SFHe in space. To prove the enabling technology the SHOOT flight demonstration will test components and the system aspects necessary for the transfer and fluid management of SFHe in orbit. Currently, components such as the cryogenic valves, quick connect fluid coupling, SFHe pumps, phase separation devices and a fluid acquisition system are being developed and tested in the laboratory. SHOOT is being readied for launch aboard the shuttle in early 1991.

ACKNOWLEDGMENTS

The author gratefully acknowledges the many helpful discussions with Goddard Space Flight Center and Ames Research Center personnel who are working on this project. This project is currently funded through the NASA Office of Space Flight.

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2. M. DiPirro and S. Castles, "Superfluid Helium Transfer Flight Demonstration Using the Thermomechanical Effect", Cryogenics 26, (1986), p.84. This issue of Cryogenics has a number of papers on the subject of helium transfer.

3. G.E. McIntosh, D. Martindale, and D.S. Lombard, "Superfluid Helium Transfer Tube Quick Disconnect", Final Report on NASA contract NAS5-29224, report #500799.

SPACE STATION POWER SYSTEMS

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MICROGRAVITY FLUID MANAGEMENT IN TWO-PHASE THERMAL SYSTEMS

A NASA-JSC PERSPECTIVE

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Initial trade studies by NASA Phase B Space Station contractors have indicated that in comparison to an all liquid single phase system, a two-phase liquid/vapor thermal control system requires significantly lower pumping power, demonstrates more isothermal control characteristics, and allows greater operational flexibility in heat load placement.

Subsequently, as a function of JSC's Work Package responsibility for thermal management of Space Station equipment external to the pressurized modules, prototype development programs were initiated on the Two-Phase Thermal Bus System (TBS) and the Space Erectable Radiator System (SERS). Proposed use of these biphase fluid systems has made it necessary for NASA and contractor engineers to better understand liquid/vapor dynamics and heat transfer characteristics during fluid change of phase in the microgravity environment.

JSC currently has several programs underway to enhance the understanding of two-phase fluid flow characteristics. The objective of one of these programs (sponsored by the Microgravity Science and Applications Division at NASA-Headquarters) is to design, fabricate, and fly a two-phase flow regime mapping experiment in the Shuttle vehicle mid-deck. Another program, sponsored by OAST, will involve the testing of a two-phase thermal transport loop aboard the KC-135 reduced gravity aircraft to identify system implications of pressure drop variation as a function of the flow quality and flow regime present in a representative thermal system. Information from each of these experiments will be used in designing a flight test article of the Prototype TBS which is to be scheduled to fly as a payload aboard the Shuttle vehicle. These experiment results will ultimately allow the Space Station Thermal Management System to be designed with engineering confidence and with increased operational efficiency.

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During the last five years, NASA-JSC has taken an active role in the development of thermal technology for spacecraft temperature control using heat pipes and two-phase fluid heat transport. This activity has highlighted the potential benefits to be realized by the utilization of two-phase fluid technology and has helped to establish thermal management as a major spacecraft design parameter. JSC's accomplishments in the thermal area were recognized by NASA and the Space Station Program by the delegation of significant responsibilities for Thermal Management of the Space Station. Phase B trade studies have substantiated the initial conclusions of NASA engineers and have emphasized the importance of developing a viable Two-Phase Thermal Management System (TPTMS) for the Space Station vehicle.

SPACE STATION THERMAL MANAGEMENT

- O JSC SPACE STATION WORK PACKAGE (WP 2) THERMAL RESPONSIBILITIES AS OF AUG. '86
  - OVERALL THERMAL SYSTEM ARCHITECTURE AND END-TO-END VERIFICATION
  - PRODUCTION OF FUNCTIONAL COMPONENTS FOR "OUTSIDE ELEMENTS"
  - PLATFORM THERMAL CONTROL SYSTEM (IN COOPERATION WITH NASA-GSFC)

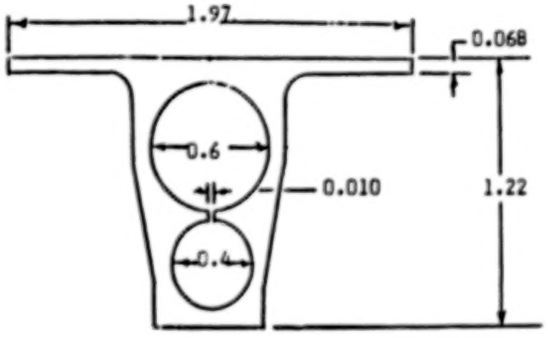
- O WP2 PHASE B TRADE STUDY RESULTS INDICATE TWO-PHASE THERMAL SYSTEMS OFFER ADVANTAGES OVER SINGLE-PHASE SYSTEMS:
  - REDUCED PUMP POWER
  - ISOTHERMAL CHARACTERISTICS
  - FLEXIBLE HEAT LOAD PLACEMENT

Figure 1

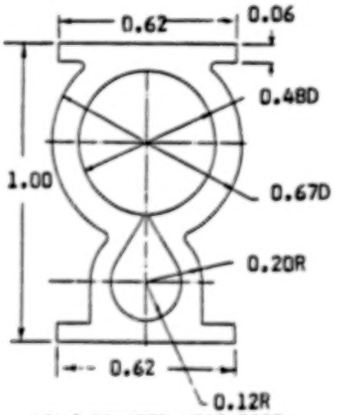
In an effort to bring the technology forward from the point of "proof-of-concept," development contracts were initiated to establish "prototype" systems concepts and to focus the hardware designs on the Space Station specifically. Parallel contracts were awarded to Grumman and LTV (with Lockheed as a subcontractor) to define space erectable radiator designs and to Grumman and Boeing (with Sundstrand as a subcontractor) to define two-phase thermal transport system designs. Although both the heat pipe radiators and thermal bus will utilize ammonia in liquid and vapor states, microgravity effects will be more significantly manifested in the thermal bus system. Therefore, the thermal transport system will be the focus of this discussion.

PROTOTYPE THERMAL MANAGEMENT SYSTEMS

- SPACE ERECTABLE RADIATORS UTILIZING HEAT PIPES
  - GRUMMAN MONOGROOVE
  - LTV/LOCKHEED TAPERED ARTERY



GRUMMAN HEAT PIPE



LTV/LOCKHEED HEAT PIPE

- TWO-PHASE THERMAL BUS
  - GRUMMAN SEPARATED PHASE, PUMPED ASSISTED CAPILLARY SYSTEM
  - BOEING/SUNDSTRAND INTEGRATED LIQUID/VAPOR PHASE SYSTEM

Figure 2

The Boeing Prototype Thermal Bus concept utilizes a Sundstrand Rotary Fluid Management Device (RFMD), accumulator, and back-pressure regulator valve (BPRV) to control liquid inventory to the evaporators. Varying quality liquid/vapor mixtures (changing as a function of heat load) exit from the evaporators and are returned to the RFMD pump. There, the rotating drum of the pump separates liquid from vapor by centrifugal forces. This causes liquid to be located at the wall of the drum, enabling a pressure head at a pitot pump intake probe. The separated liquid is again pumped to the evaporator sites. Vapor, located in the center core of the drum, exits through the BPRV to be condensed at the radiator interface using shear flow control of the condensed liquid layer thickness. The condensate is returned to the pump and regenerated to saturation temperature. The unique features of this system are the absence of active flow control hardware for the evaporators and the presence of two-phase fluid flow in the "wet" return line.

BOEING PROTOTYPE THERMAL BUS SYSTEM SCHEMATIC

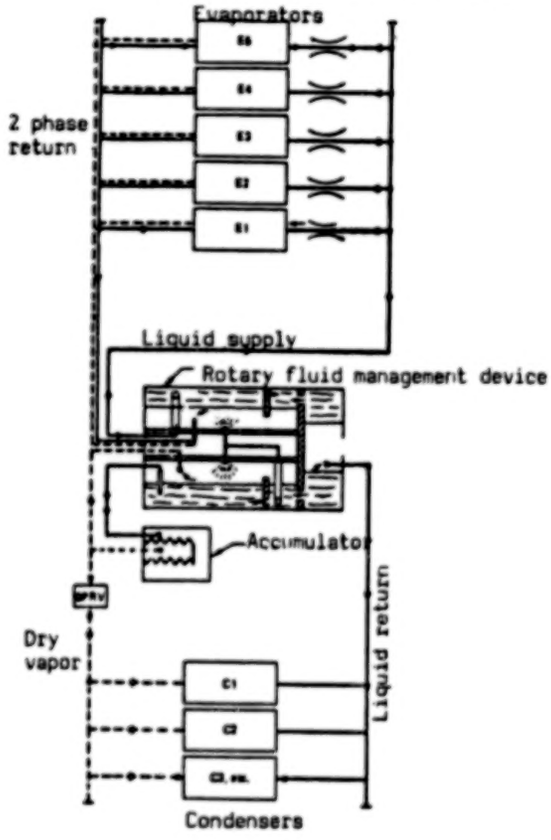


Figure 3

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Grumman eludes potential problems of fluid management in two-phase transport lines by controlling flow into the evaporators, causing only high quality vapor to be emitted. Liquid is admitted by solenoid valves to reservoirs upstream of the evaporators and is wicked by capillary forces from the reservoirs into the evaporator plates. The "dry" vapor exits the evaporators, condenses at the radiator interface, is drained by capillary action, and exits as sub-cooled liquid. The amount of sub-cooling that is required is a function of pump and system characterictics. A pump which is insensitive to cavitation will not require as much sub-cooling (to prevent vapor formation at the pump inlet). The sub-cooled liquid exiting the pump will enter a regenerator to bring the fluid back up to the saturation temperature before being admitted to the evaporator reservoirs. In actual practice the regenerator function may not be required or may be de-tuned to maintain sub-cooling for proper valve functioning. The advantages of this system are predictability (due to single phase liquid and vapor transport lines), high evaporative heat transfer coefficients, and small pump power requirements.

GRUMMAN PROTOTYPE THERMAL BUS SYSTEM SCHEMATIC

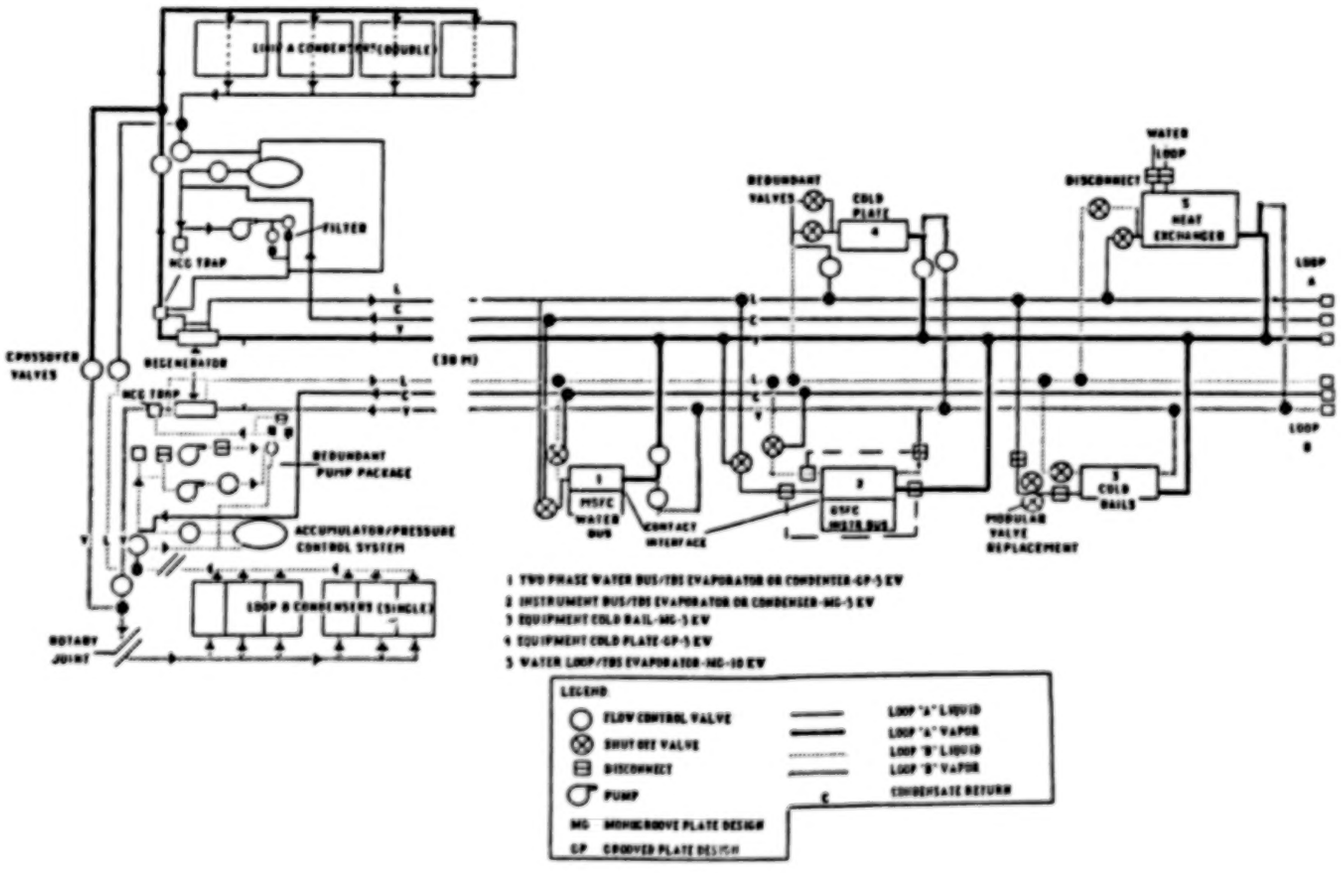

Figure 4

The design of the two-phase heat acquisition and transport system for the Space Station will be accomplished while trying to minimize the effects of gravity (or the absence thereof) on system performance. The are, however, certain aspects of fluid behavior which must be well understood to ensure adequate and efficient hardware design. Although several of these areas have been addressed in previous investigations, none has been sufficiently researched in the microgravity environment to establish a credible data base. Therefore, a continued and vigorous research program must be established so that fundamental knowledge keeps pace with, and conceivably precedes, technology development.

TWO-PHASE FLUID TECHNOLOGY REQUIREMENTS IN MICROGRAVITY

- FLOW BEHAVIOR (LIQUID/VAPOR DYNAMICS)
- PRESSURE DROP IN TWO-PHASE FLOWS OF VARYING QUALITIES
- CONDENSATION/BOILING HEAT TRANSFER COEFFICIENTS
- CHARACTERISTICS OF PHASE SEPARATION

Figure 5

An initial step in the direction of establishing a significant data base for fluid flow behavior has been accomplished by NASA-JSC in conjunction with NASA-LeRC. These two NASA centers have undertaken tentative efforts to define liquid/vapor flow regimes in the microgravity environment and to identify accompanying flow characteristics, such as pressure drop. LeRC has begun drop tower experiments to this end, and JSC has undertaken an effort to define a potential Shuttle mid-deck flight experiment. This latter activity has been funded by the Microgravity Science and Research Division at NASA-Headquarters, but due to the structure of that program, further progress may be delayed.

MULTI-PHASE FLUID BEHAVIOR IN THE MICROGRAVITY ENVIRONMENT

- O CURRENT TASK: TWO PHASE FLOW REGIME MAPPING
  - ACCOMPLISH MAPPING OF FLUID FLOW REGIMES IN REDUCED GRAVITY ENVIRONMENT
  - GRANT WITH DR.'s KESHOCK AND ARIMILLI AT THE UNIVERSITY OF TENNESSEE TO DEFINE SHUTTLE MID DECK FLIGHT EXPERIMENT
  - INITIATED JAN. '86, PRELIMINARY STUDIES HAVE BEEN ACCOMPLISHED
  - FUNDING SOURCE: MICROGRAVITY RESEARCH PROGRAM

- O SUBSEQUENT TASKS:
  - CONDENSATION/BOILING HEAT TRANSFER COEFFICIENTS
  - LIQUID/VAPOR SEPARATION TECHNIQUES

Figure 6

In an effort to obtain near-term information on the operation of two-phase fluid thermal management systems in a reduced gravity environment, JSC has contracted a task with Sundstrand to develop a test stand for incorporation of unique two-phase system components. This test stand will allow ground and KC-135 testing of an integrated advanced thermal control system and will enable photography and measurement of two-phase flow regimes with their associated pressure drops. The objective of the experiment is to confirm the operational characteristics of the unique Rotary Fluid Management Device (RFMD) concept which Sundstrand has refined under contract to JSC. This system has potential for being used in the Space Station TMS, but some uncertainty exists within the technical community as to the behavior of liquid/vapor flow regimes in the reduced gravity environment. NASA-LeRC has added supplemental funds to the effort to gather data on the shear flow controlled condensation of vapor as it would apply to a Sundstrand Organic Rankin Power System.

TWO-PHASE THERMAL MANAGEMENT SYSTEM (TPTMS) COMPONENT DEVELOPMENT

- O OBJECTIVE IS TO DESIGN AND FABRICATE TEST STAND INCORPORATING PROTOTYPE TPTMS COMPONENTS TO BE TESTED IN AMBIENT AND REDUCED GRAVITY ENVIRONMENTS
  - EVALUATE TWO-PHASE FLOW REGIMES AND PRESSURE DROPS
  - EVALUATE VAPOR CONDENSATION PROCESS IN SHEAR FLOW

- O CONTRACT WITH SUNDSTRAND ENERGY SYSTEMS FOR COMPONENT AND TEST STAND DEVELOPMENT
  - DR. KESHOCK ACTING AS CONSULTANT AND ACCOMPLISHING DATA EVALUATION
  - TEST STAND TO BE DELIVERED IN SEPT. '86; KC-135 FLIGHT SCHEDULED FOR NOV.

- O FUNDING SOURCE: OAST AND LERC SPACE STATION ADVANCED DEVELOPMENT

Figure 7

The Sundstrand TPTMS test stand will consist of the RFMD pump, accumulator, BPRV, swirl flow evaporator, and shear flow controlled condenser. An approximately 20-foot-long section of clear two-phase fluid transport line will enable high speed photography to be accomplished during ground and reduced gravity testing. The transparent line will include a 180° bend to assess its affect on fluid flow characteristics. Additionally, the condenser will have a clear outer housing to allow photography of the condensation process. Monitoring of the numerous measurement locations will be accomplished using a 14-channel analog recorder and a 50-channel desk-top type computer, which will be loaded into equipment racks for the KC-135 flight. Three flight days are planned, each of 2 1/2 to 3 hours of duration. Results of the testing are intended to confirm Sundstrand performance predictions of their TMS concept, provide insight into liquid/vapor interactions under varying flow conditions, and verify performance of shear flow controlled condensation.

SUNDSTRAND KC-135 TPTMS TEST STAND SCHEMATIC

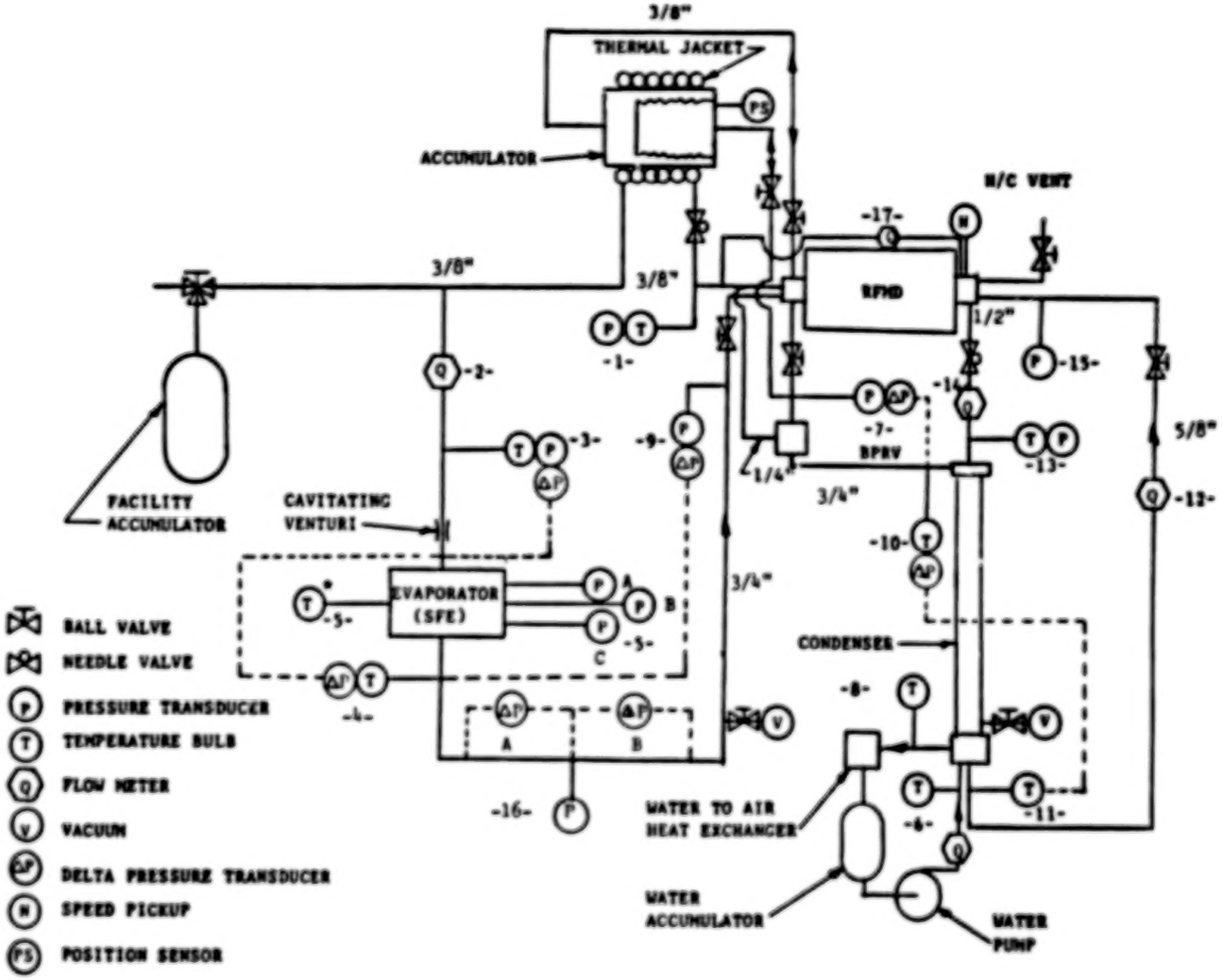

Figure 8

The ultimate step in demonstration and verification of the two-phase TMS will be accomplished through flight testing aboard the Shuttle vehicle. NASA-JSC currently has a three-phase approach to the flight experiment program demonstrating thermal performance and assembly techniques of heat pipe radiator elements and verifying thermal bus operational performance. NASA-GSFC had originally planned a TEMP 2C flight experiment to evaluate operation of either a capillary pumped Loop (CPL) or pumped two-phase (PTP) loop to be used for thermal control of the payloads and attached equipment on the Space Station. This experiment has subsequently been integrated with the TEMP 3C experiment to fly as a single payload aboard the Shuttle vehicle. Furthermore, there is currently a study being accomplished at JSC to assess the benefits or detriments of combining TEMP 3B and TEMP 2C/3C. Successful completion of these flight experiments will insure confidence in the design of hardware to be used by the Space Station.

JSC THERMAL ENERGY MANAGMENT PROCESSES (TEMP3) SHUTTLE FLIGHT EXPERIMENTS

- O DEMONSTRATE TWO-PHASE THERMAL TECHNOLOGIES IN A SPACE ENVIRONMENT
  - TEMP 3A: HEAT PIPE RADIATOR ELEMENT THERMAL PERFORMANCE
  - TEMP 3B: HEAT PIPE RADIATOR ASSEMBLY
  - TEMP 3C: TWO-PHASE THERMAL SYSTEM PERFORMANCE
- O UTILIZE JSC CONTRACTED HARDWARE DEVELOPED UNDER SPACE STATION ADVANCED DEVELOPMENT PROGRAMS
- O VERIFY HEAT TRANSFER/TRANSPORT CAPABILITIES ON-ORBIT
- O STATUS:
  - TEMP 3A MANIFESTED FOR FLIGHT
  - TEMP 3B HARDWARE AND INTEGRATION EFFORT IN PROGRESS
  - TEMP 3C EXPERIMENT DEFINED AND CONTRACT INITIATED
- O FUNDING SOURCE: SPACE STATION PROGRAM

Figure 9

SUMMARY

Utilization of multiphase fluids (liquid/vapor) in the Thermal Management System for Space Statin has numerous potential benefits. Reduced pumping power requirements, isothermal control characteristics, and flexibility in placement of heat loads are the most attractive of these benefits. Although the technology has been demonstrated in ground testing, numerous questions remain as to fluid behavior in the microgravity environment. These uncertainties include: a) fluid flow regimes and associated pressure drops; and b) evaporation, boiling, and condensation heat transfer coefficients. Systems can be designed conservatively to compensate for these uncertainties; however, for optimization of components, more detailed knowledge is required.

Activities have been initiated by NASA to obtain the required design information by utilizing the JSC reduced gravity aircraft and flight experiments aboard the Shuttle. These activities should markedly increase the data base for future design endeavors but a wealth of information on multiphase fluid behavior is still required to ensure adequate understanding of phenomena unique to the microgravity environment. It is suggested and recommended that increased activity in the area be initiated to further substantiate this technology for spacecraft thermal control.

- TWO-PHASE FLUID FOR SPACECRAFT THERMAL MANAGEMENT IS TECHNICALLY ADVISABLE
- TECHNOLOGY REQUIREMENTS HAVE BEEN IDENTIFIED
- PRELIMINARY STEPS HAVE BEEN TAKEN TO OBTAIN REQUIRED INFORMATION
  - MICROGRAVITY FLOW REGIME DEFINITION
  - KC-135 FLIGHT EXPERIMENTS
  - TEMP SHUTTLE FLIGHT EXPERIMENTS
- MICROGRAVITY INFORMATION STILL REQUIRED IN GREATER DEPTH/DETAIL
  - FUNDAMENTAL TWO-PHASE FLUID BEHAVIOR
  - HEAT TRANSFER COEFFICIENTS
  - PHASE-SEPARATION TECHNIQUES

Figure 10

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MICROGRAVITY FLUID MANAGEMENT REQUIREMENTS OF ADVANCED SOLAR DYNAMIC POWER SYSTEMS

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The advanced solar dynamic system (ASDS) program is aimed at developing the technology for highly efficient, lightweight space power systems. The approach is to evaluate Stirling, Brayton and liquid metal Rankine power conversion systems (PCS) over the temperature range of 1025 - 1400K, identify and prioritize the critical technologies and develop these technologies.

Microgravity fluid management technology is required in several areas of this program, namely, thermal energy storage (TES), heat pipe applications and liquid metal, two phase flow Rankine systems.

Utilization of the heat of fusion of phase change materials offers potential for smaller, lighter TES systems. The candidate TES materials exhibit large volume change with the phase change. A major uncertainty of TES materials operating in microgravity is void location, its impact on heat transfer and stresses and the repeatability of the storage/retrieval cycle.

The heat pipe is an energy dense heat transfer device. A high temperature application may transfer heat from the solar receiver to the PCS working fluid and/or TES. A low temperature application may transfer waste heat from the PCS to the radiator. The uncertainties of heat pipes in microgravity are startup rates, transient operation, depriming, burnout and restart capability.

The liquid metal Rankine PCS requires management of the boiling/condensing process typical of two phase flow systems.

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The objective of the ASDS program is to develop the technologies for power systems operating in the temperature range of 1025 - 1400 K and power levels of 3-300 KWe.

A current contract with Rocketdyne will identify missions, select power levels and compare the performance and specific weight of Stirling, Brayton, and liquid metal Rankine solar dynamic power systems. This will be compared with the efficiency and specific weight of Photo-Voltaic systems.

Concentrator technology is evaluating lightweight, highly accurate reflecting surfaces and refracting surfaces such as a domed Fresnel lens. Two contracts are planned for FY 87 to study advanced concentrator technology. The use of micro-sheet glass for a second surface concentrator with silver or aluminum and epoxied to an appropriate substrate is being evaluated as a separate effort. The domed Fresnel lens concentrator is currently being studied by Entech, Inc.

Advanced heat receiver designs are currently being developed on parallel contracts with the AiResearch Manufacturing Company and Sanders and Associates. An in-house materials effort is aimed at identifying TES materials which will span the temperatures of interest and conducting compatibility tests of TES and containment materials.

ASDS PROGRAM OVERVIEW

- SYSTEMS STUDIES
- CONCENTRATOR TECHNOLOGY
- HEAT RECEIVER TECHNOLOGY
- CONCENTRATOR/RECEIVER SUBSYSTEM TEST
- PCS TECHNOLOGY
- HEAT PIPE RADIATOR TECHNOLOGY
- CRITICAL TECHNOLOGY VERIFICATION IN LEO
- SYSTEM TESTS

FIGURE 1

The concentrator and heat receiver technology efforts will lead to component tests for complete characterization. Component testing will lead to a concentrator/heat receiver subsystem test.

The current systems study indicates that the liquid metal Rankine PCS resulted in a substantially higher specific mass than either the Stirling or Brayton PCS. The Stirling free piston engine is being developed at the 25 KWe level on the SP-100 program. Advanced Brayton technology will be developed via foil bearing rig tests and hot turbine tests using refractory or ceramic materials.

Heat pipe radiator technology will begin in FY 88 and be conducted at the sub-component level. Critical technology verification in LEO is in support of the TES sub-system and will be described in some detail later.

Component testing in each technology area and sub-system tests will lead to a full-up system test. The power level of the systems test will be determined from systems studies and available test facilities.

An ASDS application where microgravity fluid management technology is required is that of a solar receiver with integral TES. The mass of TES material can be reduced by utilizing a phase change material having a high heat of fusion and appropriate thermal properties. Many of the candidate salts such as LiF, NaF and MgF_2 exhibit large volume change with the phase change. The TES material is liquid when fully charged and solid with a substantial void when discharged. The location of the void, its impact on heat transfer and temperature distribution, container stresses and repeatability of the charge/discharge cycle are uncertain in microgravity.

The capability to predict the thermal performance and behavior of TES materials in microgravity and container stress levels is a critical technology for ASPS.

SOLAR RECEIVER WITH INTEGRAL TES

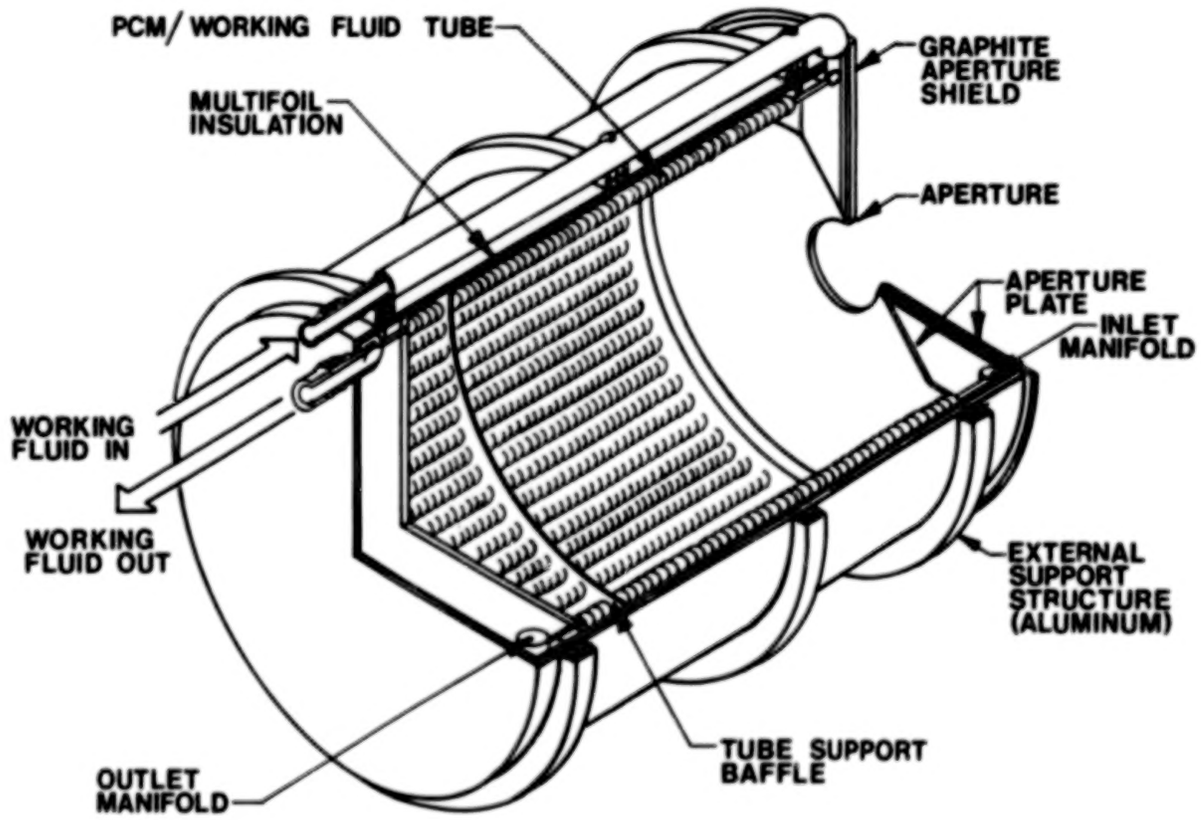


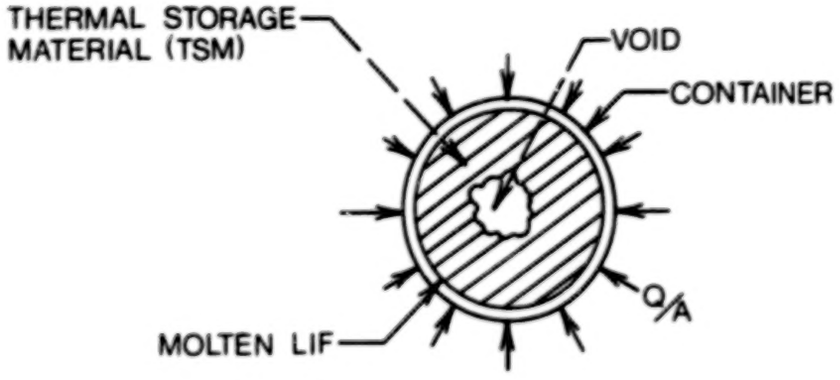
Figure 2

The stresses (thermal & mechanical), heat transfer, temperatures and void location in microgravity are dependent on configuration and the directions of heat storage and heat removal.

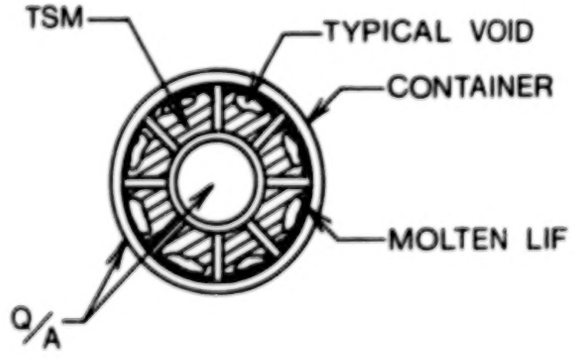
A cylindrical configuration with uniform heat addition and removal at the outer diameter is shown in Figure 3a. At the end of the discharge cycle (frozen), the void may be centrally located. On beginning the charge cycle (melting), the liquid TES expands and exerts a pressure on the TES material and containment shell. The magnitude of the stress in the containment wall depends on the relative strengths of the TES and container materials. Plastic deformation of the container could lead to a ratcheting condition and eventual failure of the container.

An annular configuration with external heat addition and internal heat removal is shown in Figure 3b. Fins are included to aid the heat transfer. At the end of the discharge cycle, the void may be located near the outer diameter of the container. Researchers anticipate that, on beginning the charge cycle, the expanding liquid will experience early communication with the void and reduced mechanical stresses.

TES CONFIGURATIONS



(a.) UNIFORM HEAT ADDITION AND REMOVAL

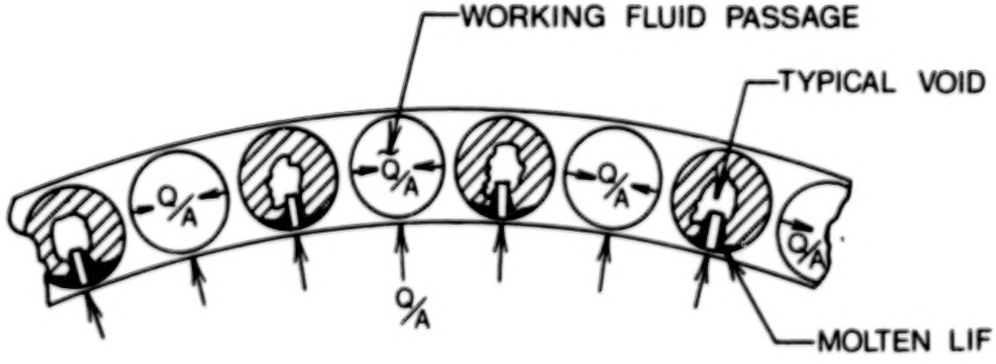


(b.) EXTERNAL HEAT ADDITION, INTERNAL HEAT REMOVAL

Figure 3

An alternate configuration shown in Figure 3c has internal heat addition and circumferential heat removal to and from the TES material. The void in the discharged TES material may be centrally located. Use of a thermal finger could provide early communication between the liquid and the void. This same concept could be applied to the cylindrical configuration.

TES CONFIGURATION



(c.)INTERNAL HEAT ADDITION, CIRCUMFERENTIAL HEAT REMOVAL

Figure 3 Continued.

The capability to design and operate TES subsystems in microgravity is a critical technology for ASPS. Verification of this technology in microgravity is necessary. A program has been planned which will develop and verify this technology in LEO.

An initial effort is the development of a computer program for transient thermal and stress analysis of TES materials operating in microgravity, including location of the void. Two approaches are being considered: a completely rigorous solution and an approximate solution. The approach selected will be consistent with the schedule requirements of the program.

Technology verification will be established by four flight experiments spanning the temperature range of interest.

Flight tests will be preceded by the design phase and extensive ground testing of each experiment to establish its thermal performance and flight capability. Safety of the experiment will be emphasized.

TES CRITICAL TECHNOLOGY VERIFICATION IN LEO

- DEVELOP COMPUTER PROGRAM FOR TRANSIENT THERMAL AND STRESS ANALYSIS OF TES MATERIALS IN MICROGRAVITY
- GROUND TESTS - PERFORMANCE AND FLIGHT QUALIFICATION OF 2-4 PROTYPICAL TES SPECIMENS
- FLIGHT TESTS - 2 - 4 TES SPECIMENS USING "GAS" OR "HITCH-HIKER" AS CARRIER
- POST FLIGHT EVALUATION - COMPARISON WITH ANALYTICAL PREDICTIONS
- TECHNOLOGY VERIFICATION

FIGURE 4

The flight experiments will be flown on the shuttle using the "Get-Away-Special" or "Hitch-Hiker" with opening lid containers. Each TES experiment will be subjected to 10 melt/freeze cycles closely approximating orbit times of 60/34 minutes of sun/shade, with prototypical heating rates and configurations. Thermal instrumentation with data acquisition and storage will define the transient thermal operation of the TES experiments. Post test sectioning will establish the void location. Correlation of predicted thermal performance and void location with flight results will verify this technology.

The heat pipe is an energy dense heat transfer device which utilizes the heat of vaporization and condensation of a working fluid. Heat is transferred at near isothermal conditions in this device. There are both high and low temperature potential applications of the heat pipe in ASDS.

A high temperature application of the heat pipe may be to transfer heat from the heat receiver to the heater head of a Stirling engine. A similar application exists for the solar dynamic Brayton engine.

Heat pipes and capillary pumped loops have operated in microgravity. The location of the working fluid is easily controlled in the 1g environment so that initial startup in microgravity will find the evaporator section with ample working fluid. Even so, the following uncertainties in microgravity exist:

- o Transient operation and analysis
- o Fast startup; burnout
- o Restart capability
- o Depriming - Vibrations or Accelerations

POTENTIAL HEATER MODULE — HEAT PIPE ARRANGEMENT

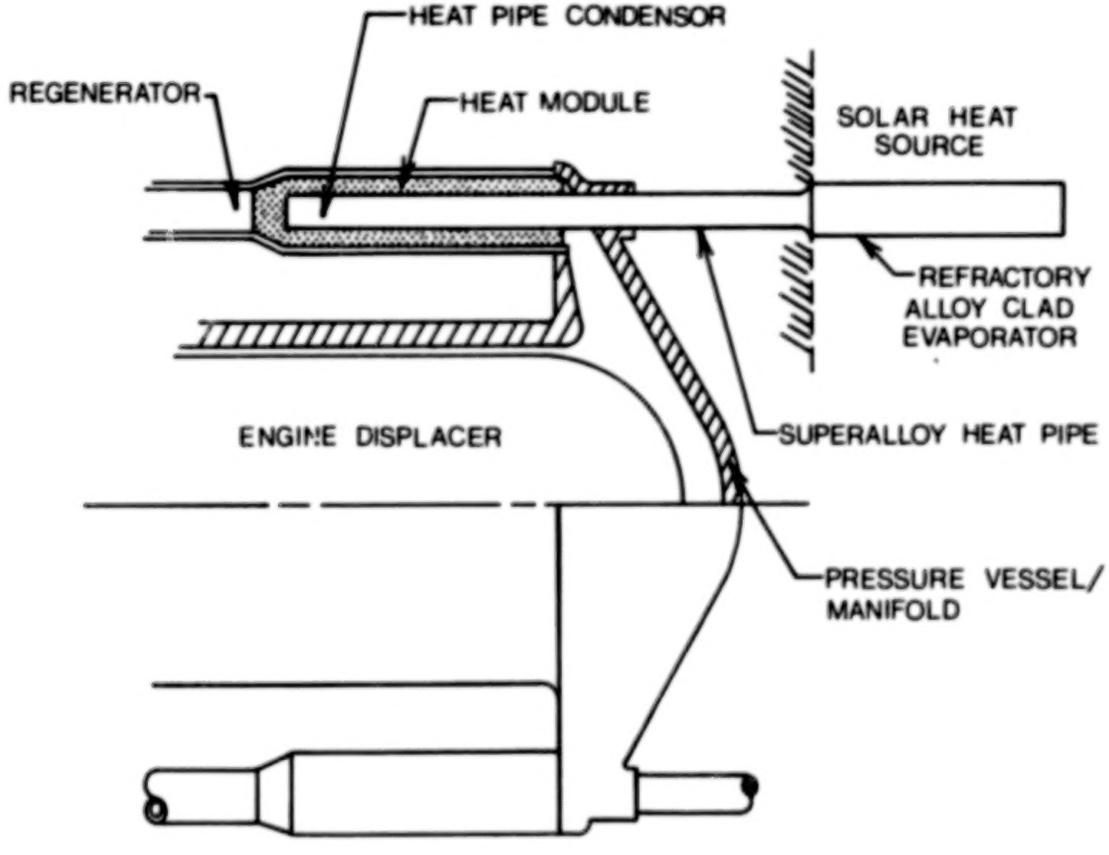


Figure 5

A low temperature application of the heat pipe may be to transfer waste heat from the power conversion system to and throughout the radiator. The concept shown below utilizes a pumped liquid loop (thermal bus) and heat pipes for transfer of heat to a number of finned panels.

The major concerns of the low temperature heat pipe are those discussed previously.

HEAT PIPE RADIATOR CONCEPT

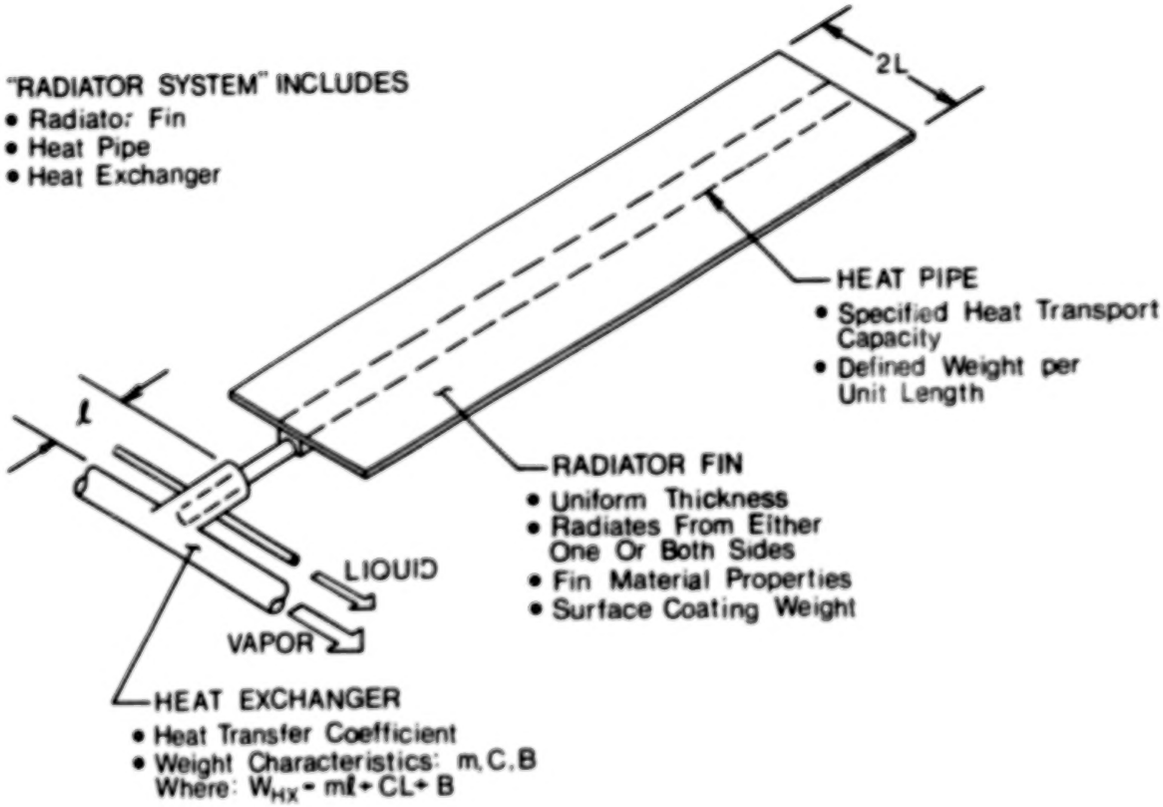


Figure 6

The heat pipe technology program of LeRC is still in a planning phase with certain program elements initiated. The procurement of an advanced radiator concepts study and the development of computer programs for steady state performance analysis have been initiated.

Sub-component development will include investigation of metal and ceramic composites as heat pipe structures, coating and surface treatments, wicking systems and capillary channels. Development of processing requirements will characterize contaminants, develop gettering systems and provide the procedures for cleaning, outgassing, filling and closing of heat pipes.

Life prediction will require the development of a life model and computer code. This model will be developed utilizing a data base of heat pipe experimental life data. In addition to the steady state performance analysis, transient analysis capability is required and will be developed.

Microgravity testing of heat pipes has not been included in the plan at this time. Further study of transient operation and restart in microgravity may lead to microgravity testing.

HEAT PIPE TECHNOLOGY PROGRAM

- ADVANCED RADIATOR CONCEPTS - CONTRACTOR
- SUB-COMPONENT DEVELOPMENT - IN-HOUSE
- PROCESSING REQUIREMENTS
- LIFE PREDICTION AND TESTING
- PERFORMANCE CODES - STEADY STATE AND TRANSIENT

FIGURE 7

The Rankine PCS was a third candidate for ASDS. However, the systems study at Rocketdyne has indicated that the Stirling and Brayton ASDS are more attractive than a liquid metal Rankine system on a specific weight basis. The Rankine PCS will therefore not be emphasized in the ASDS program.

The Rankine PCS is a viable candidate for the nuclear power system. The microgravity fluid management technology required for a boiling/condensing power system will be addressed by Dr. Antoniak.

TWO LOOP L.M. RANKINE SYSTEM

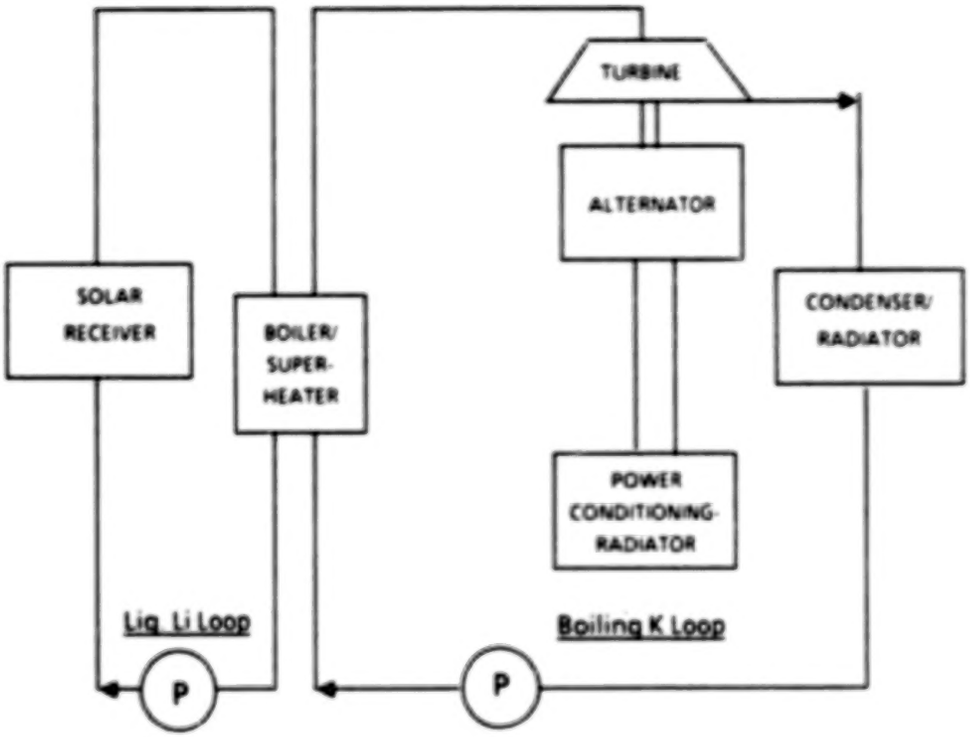


FIGURE 8

SUMMARY

The advanced solar dynamic power technology program considered three candidate power conversion systems: Stirling, Brayton and Liquid Metal Rankine. Each of these solardynamic power systems involves a microgravity fluid management technology.

A solar dynamic power system (SDPS) operating in a low earth orbit (LEO) requires an energy storage system if continuous power is to be provided over the entire sun/shade orbit. Thermal energy storage (TES) utilizing the heat of fusion of a salt such as LiF offers the potential for lightweight energy storage systems. However, the salts exhibit a large volume change (20 - 30%) on melting during heat addition. When the salts freeze during heat removal, they introduce a void. To design such systems for operation in space, one must be able to predict the shape and location of the void in microgravity on a transient basis and its impact on heat transfer and TES container stresses.

The heat pipe is an energy-dense heat transfer device, which requires no external pumping power to circulate the heat transfer fluid. Heat pipes may find application to SDPS in transferring heat from the receiver to the Sterling engine, in smoothing out temperature distributions within the heat receiver, or in transferring reject heat to the radiator. Low temperature heat pipes have operated in space on the shuttle. High temperature heat pipes must be properly designed and are expected to operate in the microgravity. The major uncertainties of heat pipes in microgravity are fast startup and potential burnout, restart capability, and depriming due to vibrations or accelerations. Thus, fluid management in microgravity is an important technology for heat pipe applications.

The liquid metal Rankine power system is a two-phase flow system where the liquid metal is boiled in the heat receiver and vapor is passed through a turbine where work is extracted; the vapor must then be cooled and condensed in a condenser or radiator. A net positive suction head is required at the pump circulating the liquid metal. Again, fluid management in microgravity is an important technology. Based on systems analysis, the liquid metal Rankine SDPS is not competitive with Stirling and Brayton. However, it is attractive for the nuclear power system so the microgravity technology may be required there.

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TWO-PHASE REDUCED GRAVITY EXPERIMENTS FOR A SPACE REACTOR DESIGN

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Future space missions researchers envision using large nuclear reactors with either a single or a two-phase alkali-metal working fluid. The design and analysis of such reactors require state-of-the-art computer codes that can properly treat alkali-metal flow and heat transfer in a reduced-gravity environment. New flow regime maps, models, and correlations are required if the codes are to be successfully applied to reduced-gravity flow and heat transfer. General plans are put forth for the reduced-gravity experiments which will have to be performed, at NASA facilities, with benign fluids. Data from the reduced-gravity experiments with innocuous fluids are to be combined with normal gravity data from two-phase alkali-metal experiments. Because these reduced-gravity experiments will be very basic, and will employ small test loops of simple geometry, a large measure of commonality exists between them and experiments planned by other organizations. It is recommended that a committee be formed, to coordinate all ongoing and planned reduced gravity flow experiments.

INTRODUCTION

The Pacific Northwest Laboratory (PNL) of the Department of Energy (DOE) has been assigned the role of modeling the thermal-hydraulics of advanced multimegawatt (MMW) nuclear reactors. Various reactor concepts are being proposed by other DOE National Laboratories and by industry. This paper addresses the experimental requirements posed by one concept--where the reactor working fluid is a boiling alkali metal.

Future space missions envision the need for high power levels (up to hundreds of MWe), which are orders of magnitude greater than required by spacecraft launched previously. The concept that appears to have the best potential for supplying such power is a nuclear reactor-based one, with a heat engine and alternator providing the conversion of thermal to electrical power. Stringent weight, heat transfer, and compactness criteria lead to the use of an alkali metal heat transfer medium, with a boiling alkali metal (BAM) system offering significant advantages over a single-phase system with an intermediate heat exchanger. In any event, there is a crucial need for analytical tools that can simulate two-phase flows in a zero gravity (0-g) or variable gravity environment. Mature computer codes exist that consider single-phase liquid metal flow and two-phase steam-water flow, both in normal gravity. To be completely useful for the design and analysis of BAM reactors these codes will need to be modified to handle boiling alkali metals instead of water and to do it in variable gravity. Experimental 0-g two-phase flow data are needed to provide new models and correlations for flow regimes, drag, and heat transfer.

Code Assessment and Changes Required for Modeling 0-g Convection

Code Limits No. Phases	Validity of "Uncorrected" Run at 0 g	Estimated Trend of "Uncorrected" Values of		Modifications Required			
		Pressure Drop	Heat Transfer	Flow Regime	Friction Factor Correlation	Heat Transfer Correlation	Turbulence Intensity
1	Good[a]	Same	Same	No	No[d]	No[d]	No[d]
2, Homogeneous	Good[b]	Underpredicted	Overpredicted	No	Yes	Yes	No
2, Multifield	Poor	Underpredicted	Overpredicted	Yes	Yes[c]	Yes[c]	Yes

(a) For single-phase flow.

(b) Where homogeneous representation is applicable.

(c) Magnitude of changes depends on effect of flow regime correlations.

(d) No modifications needed at high flow rates. Possible changes at low flow where 1-g buoyancy effects could dominate.

TABLE 1

Data on alkali metal two-phase forced convection in a normal gravity field are extremely limited; reduced-gravity data are practically nonexistent (only mercury condensation has been studied somewhat). However, reduced-gravity experiments with two-phase flow of more common fluids (e.g., water, air/water, halocarbons) have been more numerous. A comprehensive literature survey of these experiments has been completed. Results of this survey indicate that both the nature of boiling alkali metal and reduced-gravity experiments and the acquired data have been limited in various ways. Thus the utility of these past experimental efforts to the design and analysis of a space reactor is marginal, and new experiments will have to be performed.

A number of other organizations are pursuing reduced-gravity experimentation, for MMW and other projects. Many of the planned experiments seek similar data, using similar fluids, test equipment, and NASA facilities. Cooperation among experimenters would benefit everyone.

FACILITIES AVAILABLE FOR REDUCED-GRAVITY EXPERIMENTS

Ideally, a manned, orbiting space station would be available with extensive laboratory facilities for reduced-gravity research. Also, launch costs, as well as the costs of developing space-qualified test hardware, would be reasonable in terms of the resulting data. Neither criterion is met currently. Small, low-power experiments could be performed on the shuttle albeit with nonhazardous fluids. The competition for the scheduled shuttle flights was keen in the past, and tests had to be planned years in advance of actual flight. With the recent grounding of the shuttle fleet pending development of reliable booster seals, only conjectures can be made regarding the timing of a shuttle experiment. Sometime in the 1990s a permanent manned orbiting laboratory may become available. At this time it is not clear if any alkali-metal experiments would be permitted there; hazardous materials are taboo on the shuttle. Regarding launch and test development costs, no appreciable cost reduction is foreseen in the near future.

Given the situation described, shuttle experiments probably will not be performed within the time frame allotted for two-phase reduced-gravity experiments. For the majority of the experiments, earth-based facilities such as drop towers and aircraft will have to be employed. These present various limitations--the chief ones being the duration and steadiness of the reduced-gravity environment. Another set of constraints is imposed by scheduling and cost restrictions. The latter provide a strong incentive for cooperation among organizations involved in reduced-gravity experiments.

PROPOSED TWO-PHASE REDUCED-GRAVITY EXPERIMENTS

The twin issues posed by experimental facility limitations and the difficulties inherent in working with alkali metals must be squarely faced by any realistic test program. Thus, the only viable approach is to perform, to the maximum possible extent, experiments with innocuous fluids such as air, water, and

Freon in place of the alkali metals. Only if the desired data were to be seriously flawed by replacement fluids will alkali metals themselves become the working fluids. At this time the feeling is that perhaps alkali metals might be acceptable for use in drop towers and the KC-135 aircraft, but they would present an unacceptable hazard in any other reduced-gravity test facilities.

The objective of the first experiment conceived here is a narrow one: to obtain data on two-phase flow regimes and pressure drop. This can be met through the use of an air-water mixture in a suitably instrumented test section. It is planned to perform most of the tests in the NASA/Lewis Research Center (LeRC) 5.2s drop tube, which is evacuated to 10^{-2} Torr prior to a test. However, because a large number of tests is foreseen, the small 2.2s drop tower will also be used in conjunction with the large drop tube. This tower is open to the atmosphere, and even when a drag shield is employed, the attainable g-level is approximately 10^{-3}, versus $<10^{-5}$ for the tube. The high g-level, plus the short duration of freefall, may limit the utility of the 2.2s facility.

The experiment, depicted in Figure 1, will consist of a series of tests, done at various mass flow rates and qualities to accomplish a full mapping of zero-g adiabatic phenomena. It is anticipated that useful correlations of several important parameters will result; Table 2 lists those of interest. Data for the correlations will be provided by instruments and cine/video film records. The measurements will consist of pressures, mass flow rates, velocities, and void fractions; flow regimes will be obtained from the films.

The intent here is initially to map the flow fields against various parameters. Thus the quality and/or void fraction data will be graphed versus the total mass velocity, and versus ΔP. The flow regimes associated with these parameters will be superimposed on the plots. Flow pattern maps will also be plotted. These maps will be compared, at 1-g and zero-g conditions. Trends ought to be evident, suggestive of which existing pressure drop correlation might be modified or corrected to extend its applicability to low-gravity situations. In the simplest case of homogeneous flow, a correlation might be of the form

$$-\left(\frac{dp}{dz}\right)_{\text{2-phase}} = -\left(\frac{dp}{dz}\right)_{\text{1-phase}} \phi^2 \quad (G,X,P, \text{ etc.})$$

where ϕ^2 is known as the two-phase frictional multiplier.

Desired Correlations

Parameter	Function of
ΔP	G, X, flow regime, Fr, Bo
ϕ	ΔP_{liquid}, Re, G, α, Bo
α	Fr, flow regime, X, Bo
Flow regime	G, X, Fr, α, Bo
K_I	G, α, flow regime, Fr

Nomenclature

G = mass velocity, kg/s m^2

X = quality, $\dot{m}_{vapor}/\dot{m}_{total}$ (-)

ϕ = two-phase pressure loss multiplier (-)

α = void fraction (local volume fraction), V_v/V_{total} (-)

Fr = Froude number, v^2/Dg (-)

Re = Reynolds number, vD/ν (-)

K_I = interfacial friction coefficients(-)

Bo = Bond number, $\rho D^2 g/\sigma$

TABLE 2

For advanced two-fluid two-phase flow models, the improved flow regime characterization along with pressure drops and (if possible) void measurements will help to develop improved models for interfacial drag. The nature of this adiabatic experiment, as well as of similar experiments exploring heat transfer and critical heat flux, is a fundamental study of heat transfer and fluid

flow phenomena. While these experiments have a definite goal, the data resulting from them ought to have broad applicability.

In fact, commonality with another experimenter has already been determined. A condensation experiment currently being performed by Texas A&M University on the KC-135 aircraft at Johnson Space Center (JSC) incorporates a boiler supplied by PNL. This boiler is instrumented to permit measurement of flow and heat transfer within it. This results in a net gain to both participants. Texas A&M University obtains the condensation data it seeks, while PNL simultaneously obtains some of the boiling data that it requires. The willingness of Texas A&M University to share its experiment with PNL has allowed us to acquire data well in advance of what the original plan, indicated on Figure 2, stipulated.

Adiabatic Air-H_2O ΔP and Flow Regime Experiment

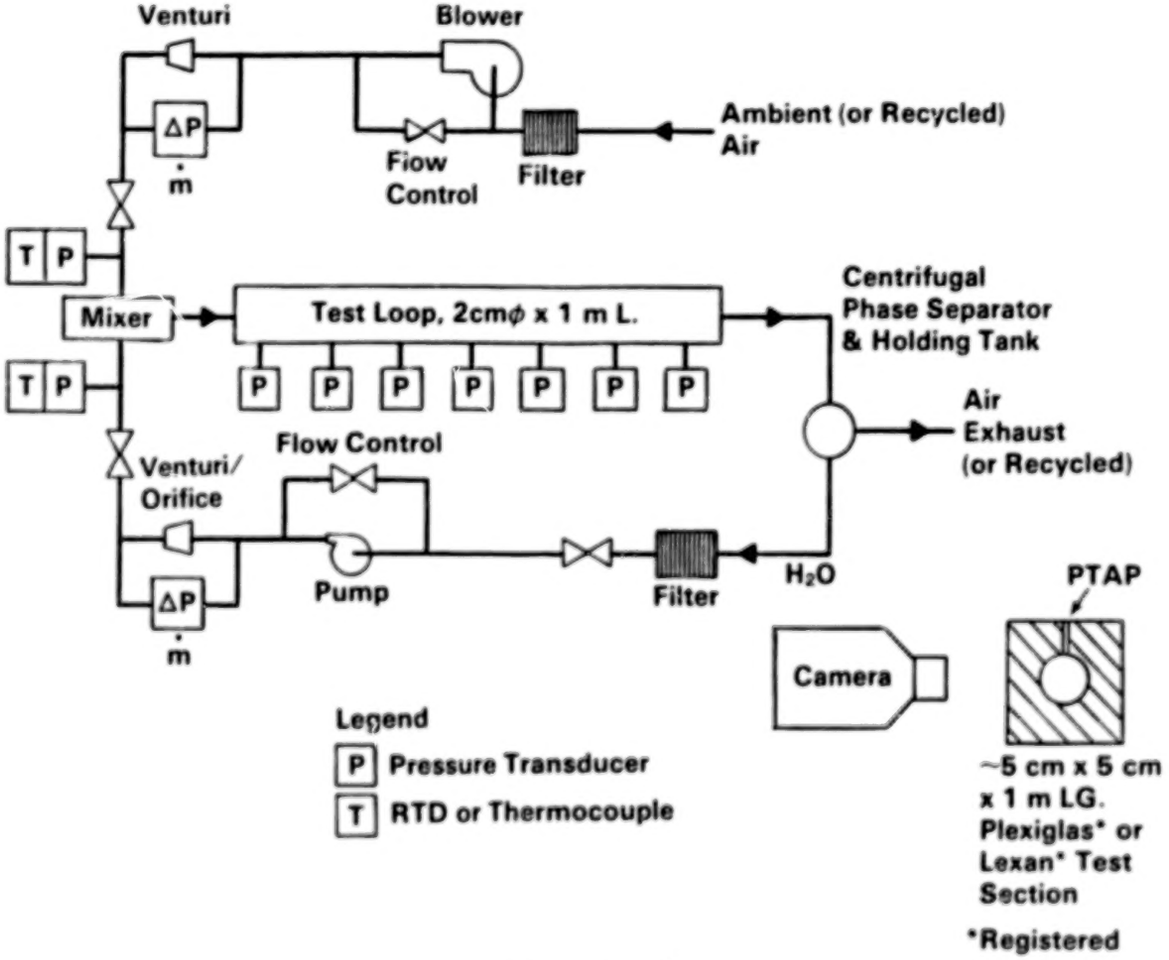

FIGURE 1

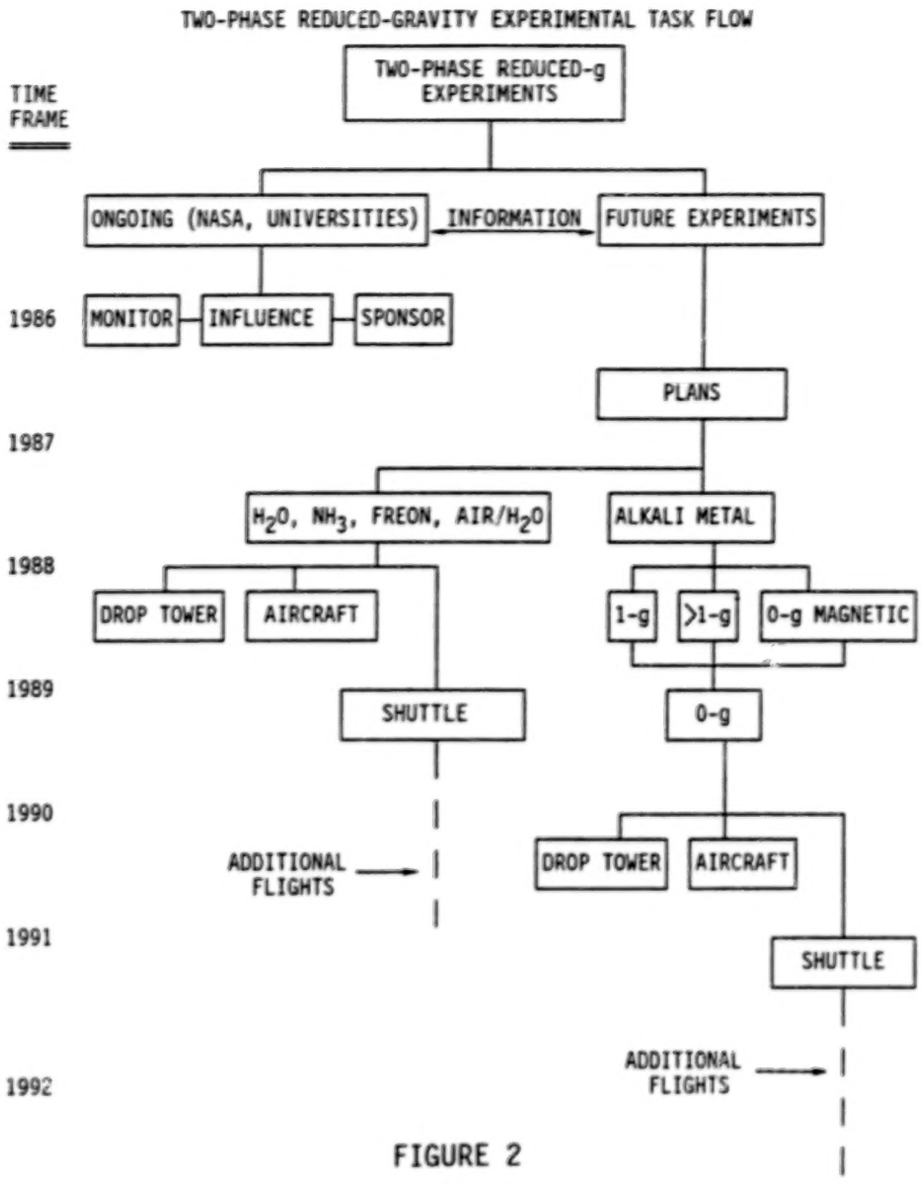

FIGURE 2

SUMMARY

The MMW thermal-hydraulic reduced-gravity two-phase experiments, as described herein, will initially seek very basic information. These experiments will employ ordinary fluids and small test loops with simple geometries. The data obtained with these loops ought therefore to be of interest to other organizations and programs, which suggests that benefits would accrue to all participants in reduced-gravity research if experiments were coordinated. Currently, there exists no means for doing so. An example of the synergism possible is provided by the cooperative experiment by Texas A&M and PNL, as cited.

We highly recommend that a coordinating committee be formed, under Lewis Research Center's aegis. This committee would ensure sharing of information, tests, and data among all reduced-gravity researchers. We at PNL would like to participate in, and work with, such a committee.

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MAINTENANCE EVALUATION FOR SPACE STATION LIQUID SYSTEMS

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Hamilton Standard
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Many of the thermal and environmental control life support subsystems as well as other subsystems of the Space Station utilize various liquids and contain components which are either expendables or are life-limited in some way. Since the Space Station has a 20-year minimum orbital lifetime requirement, there will also be random failures occurring within the various liquid-containing subsystems. These factors as well as the planned Space Station build-up sequence require that maintenance concepts be developed prior to the design phase. This applies to the equipment which needs maintenance as well as the equipment which may be required at a maintenance work station within the Space Station.

This paper presents several maintenance concepts for liquid-containing items and a flight experiment program which would allow for evaluation and improvement of these concepts so they can be incorporated in the Space Station designs at the outset of its design phase.

Introduction

The general goals for liquid-containing systems are to minimize liquid loss and gas ingestion as well as contaminant inclusion during all maintenance operations. Liquid loss should be prevented or minimized to preclude a recharge operation with the attendant need for replacement liquid and to minimize spillage which could induce other component failures, introduce possible contamination or crew safety problems, or require different, complex and time-consuming cleanup operations. Contaminant inclusion can adversely affect system operation by increasing system filter and contaminant toleration requirements. Gas ingestion should also be prevented or minimized, because it could significantly increase the requirements of gas separation equipment and could introduce the need for special evacuation or bleeding equipment.

These concerns are less significant when the liquid is water but become very significant if the liquid is hazardous, has a high vapor pressure, or if the liquid system is external to the pressurized volume of the Space Station. This paper mainly addresses the more significant cases requiring special maintenance features. The flight experiment should help determine which cases need special solutions as well as prove the acceptability of the solutions.

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Background

Due to the difficulty of, and special equipment required for draining and later recharging an entire system in zero-g, the recommended safe method for system and individual component replacement is to isolate the item or small group of items to be replaced at each of its liquid interfaces prior to removal and replacement as shown in Figure 1.

GENERAL REPLACEMENT STEPS

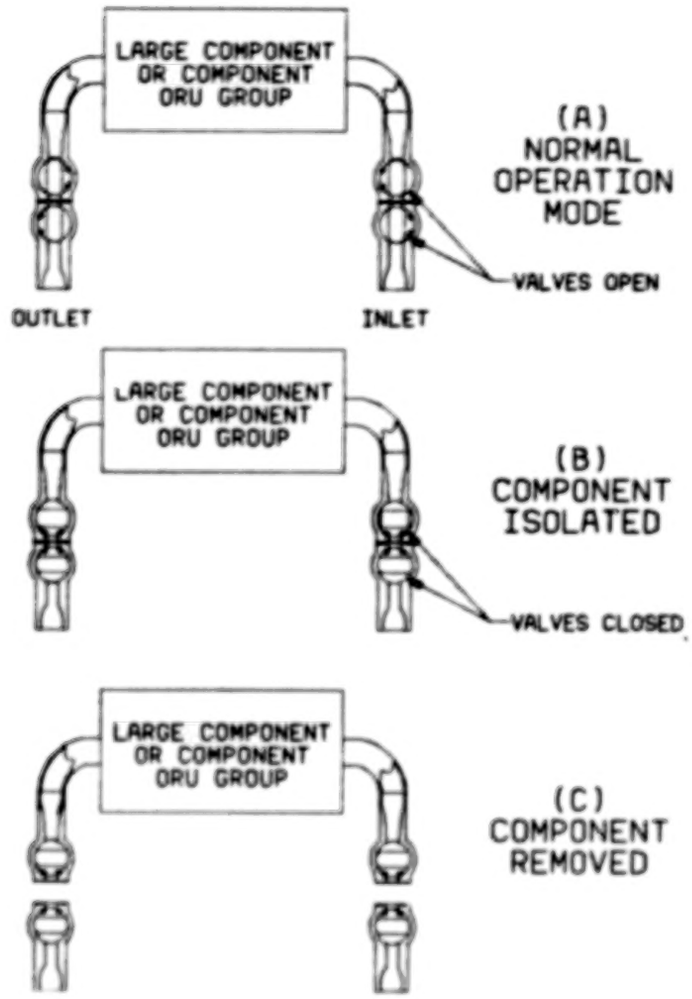


Figure 1

Because there will be at least hundreds and maybe thousands of maintenance isolation devices in the Space Station, they will have an impact on the total reliability and therefore they must themselves meet the maintenance requirements of the Space Station. Some of the basic considerations for the isolation devices are specified in Table 1.

DISCONNECT DESIGN CRITERIA

- Positive Isolation of the Fluid Loops
  - Minimum liquid spillage
  - Minimum air and contaminant inclusion
- Maintainable in Place (All Seals and Dynamic Parts)
  - No drainage and recharge
  - No depressurization required
  - Minimum system interference
- Operable in Zero-g While Suited
- Low Impact
  - Small
  - Light weight
  - Low pressure/power losses
  - Allow for assembly tolerances
  - Simple
  - Inexpensive
  - Reliable
- Common for All Applications
  - Minimize non-recurring costs
  - Minimize crew training
  - Minimize spares

Table 1

Many approaches have been studied and developed by Hamilton Standard and others, which combine the functions of isolation valves and maintenance disconnects and meet many, but usually not all, of the above considerations. Several of the key basic concepts are shown in Figures 2A and 2B. Fittings are simple, small and inexpensive, but do not provide positive isolation; relying instead on the surface tension of the fluid to prevent spillage. The quick disconnect is complicated, has high pressure drop, is sensitive to contamination, and due to its many dynamic parts is somewhat unreliable. The contamination and reliability problems compound themselves due to the fact that it is not possible to maintain quick disconnects without draining the lines.

MAINTENANCE DISCONNECT CONCEPTS

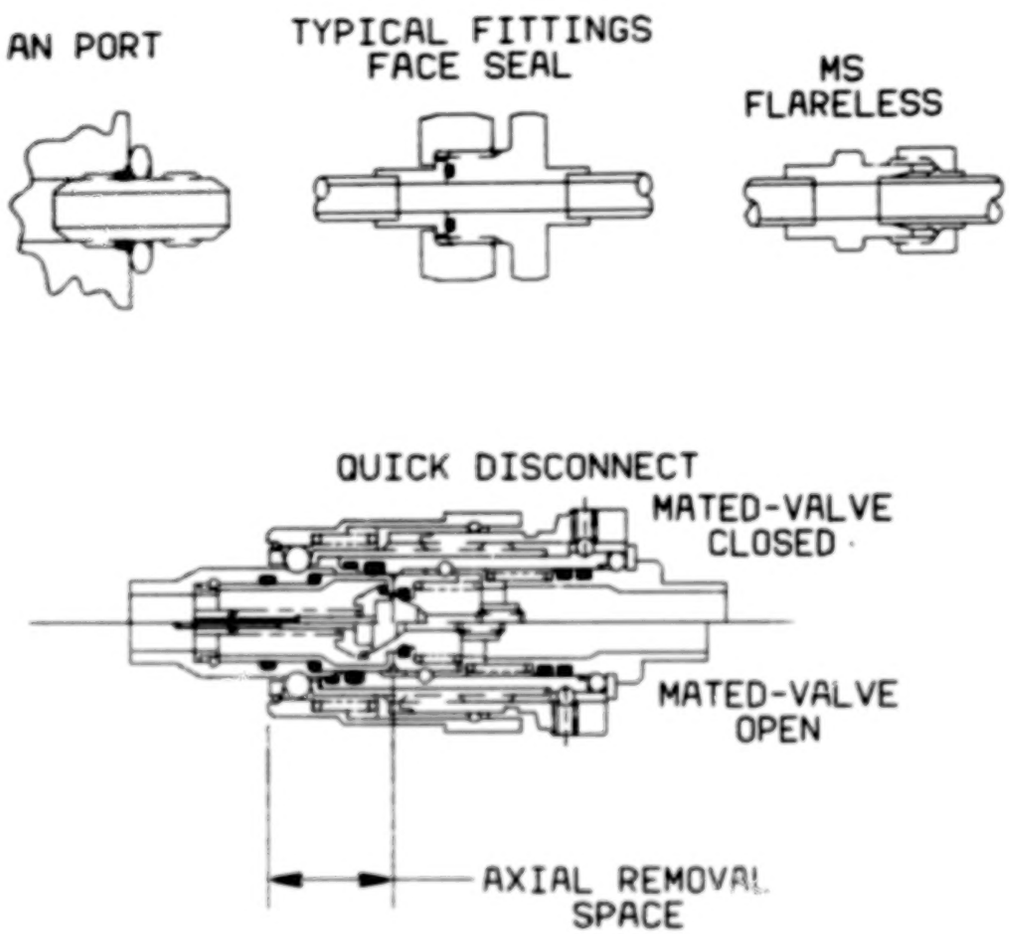


Figure 2A

The poppet and interlocking spheres positive isolation disconnects developed especially for zero-g maintenance are also not maintainable. The poppet concept has high pressure drop and the interlocking spheres concept requires accurate alignment tolerances and a significant axial separation motion. Neither is maintainable without line depressurization/drainage and both have many moving parts and stagnant fluid volumes in which contamination or precipitation can accumulate or bacteria can grow. The Maintainable Maintenance Disconnect Valve (MMDV) utilizes maintainable cylinders. This valve eliminates the problems of those above, but has a small potential spillage volume.

MAINTENANCE DISCONNECT CONCEPTS (Continued)

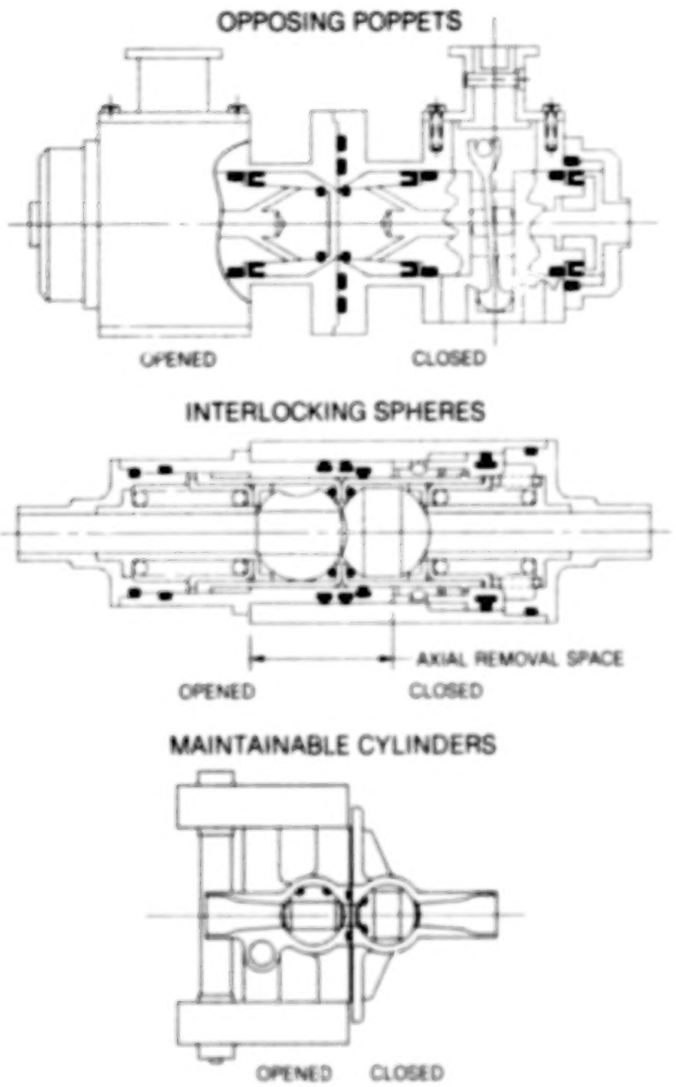


Figure 2B

Universal Applications

Various versions of the MMDV have been developed which address all of the considerations mentioned earlier. Other features such as alternate attachment techniques, ganging into multivalved manifolds, and the incorporation of various degrees of safety interlocks and redundant seals have been evaluated. Figure 3 shows an MMDV incorporating some of these features. All of these versions consist of two valves utilizing identical cylindrical cartridges and sleeves that permit servicing and replacement of all seals and moving parts with a minimum effect on system function, i.e., system pressure can be maintained and system flow will be only momentarily interrupted. As the separation plane is flat, the pair can be separated with any combination of axial or radial motion.

MAINTAINABLE MAINTENANCE DISCONNECT VALVE PAIR

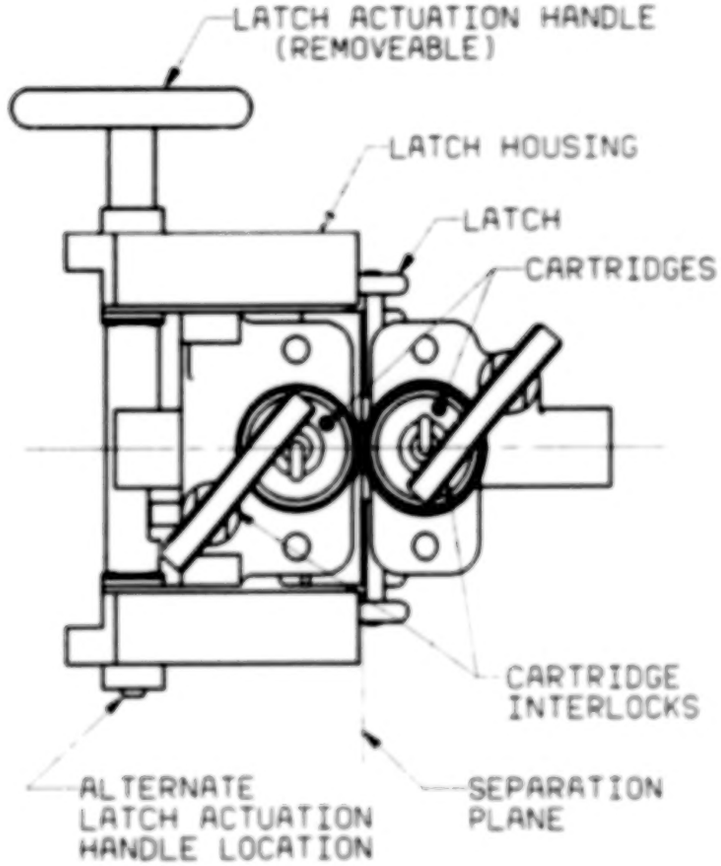
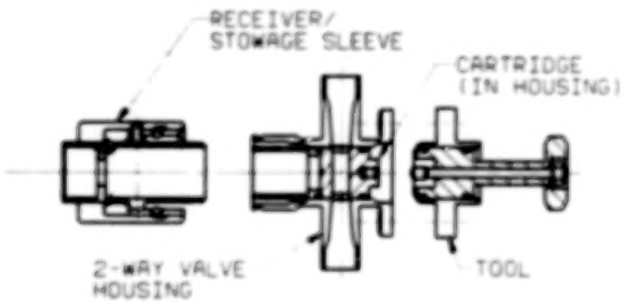


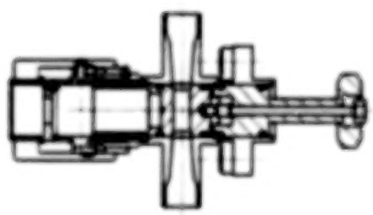
Figure 3

Figure 4 shows a 2-way application of this valve and illustrates cartridge removal. A push/pull tool and a receiver/stowage sleeve are mated to the valve housing. A central screw thread in the tool engages the cartridge. Actuation of the tool pushes the used cartridge into the receiver sleeve with no spillage of liquid. The sleeve with the used cartridge is then removed and replaced with a new sleeve containing a new precharged cartridge. The tool is now used to pull the new cartridge from the sleeve and position it in the valve housing. Removal of the tool and the sleeve completed the cartridge servicing. The cartridge concept was applied extensively to promote the maintainability of the Environmental Control and Life Support (ECLS) system developed by Hamilton Standard for the NASA Space Station Prototype (SSP), in 1972. Several improved versions of the valve have been produced since the basic concept was proven in SSP. These versions have reduced size and weight and have incorporated various degrees of seal redundancy and operational safety.

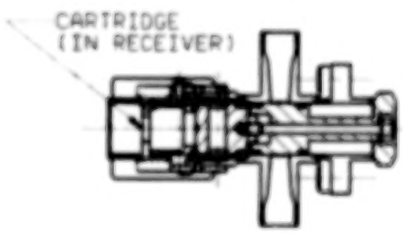
EASY CARTRIDGE REMOVAL



(A) CARTRIDGE IN HOUSING



(B) RECEIVER SLEEVE & TOOL INSTALLED



(C) CARTRIDGE IN THE RECEIVER SLEEVE
AND READY FOR REMOVAL

Figure 4

The MMDV cartridge concept also has many other applications as a maintenance feature on valves and other components. Conventional valves are replaced by a single housing (see Figure 4) similar to a MMDV housing with the cartridge configured to act as a 2-way, 3-way, or proportional flow control valve, among others, or configured to house a check valve, relief valve, or any other small items which can fit within the cartridge. Figure 5 shows several of these applications. The accumulator version allows for shut-off of trapped fluid volumes. When in the shut-off mode, the accumulator comes on line and allows for thermal expansion of the trapped liquid without significant and potentially damaging pressure increases.

CARTRIDGE WITH MULTI-FUNCTIONS
(In addition to shut-off mode)

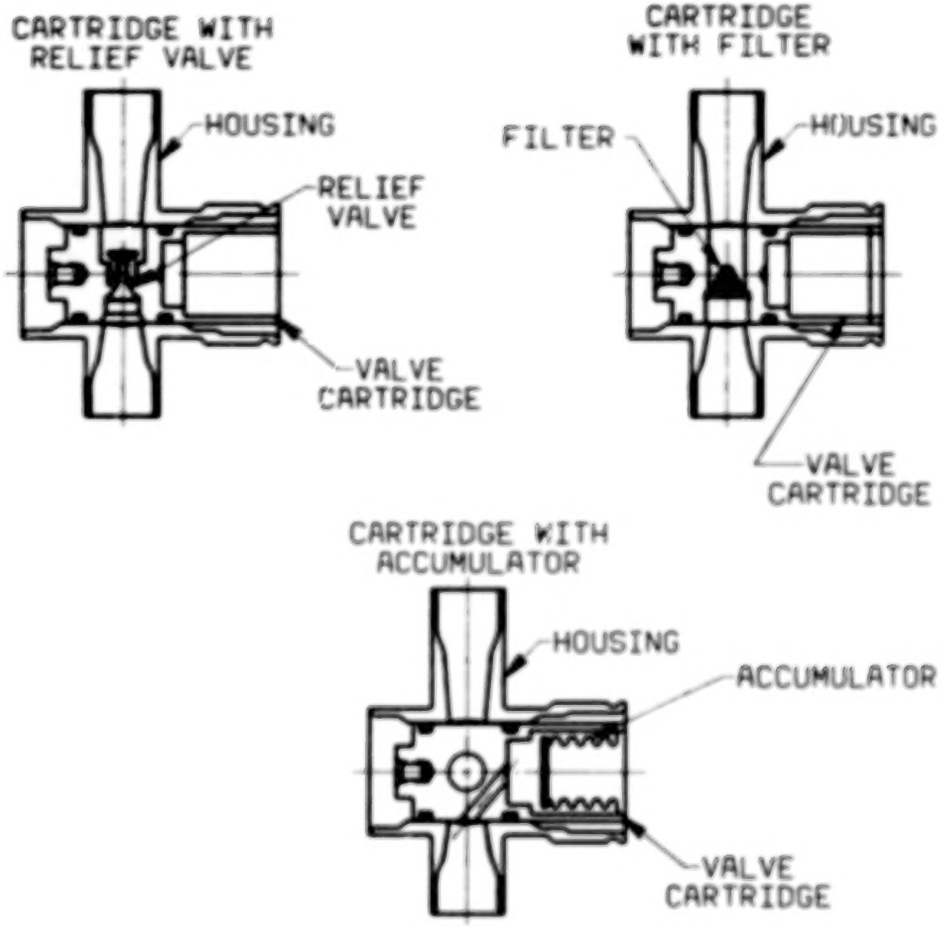
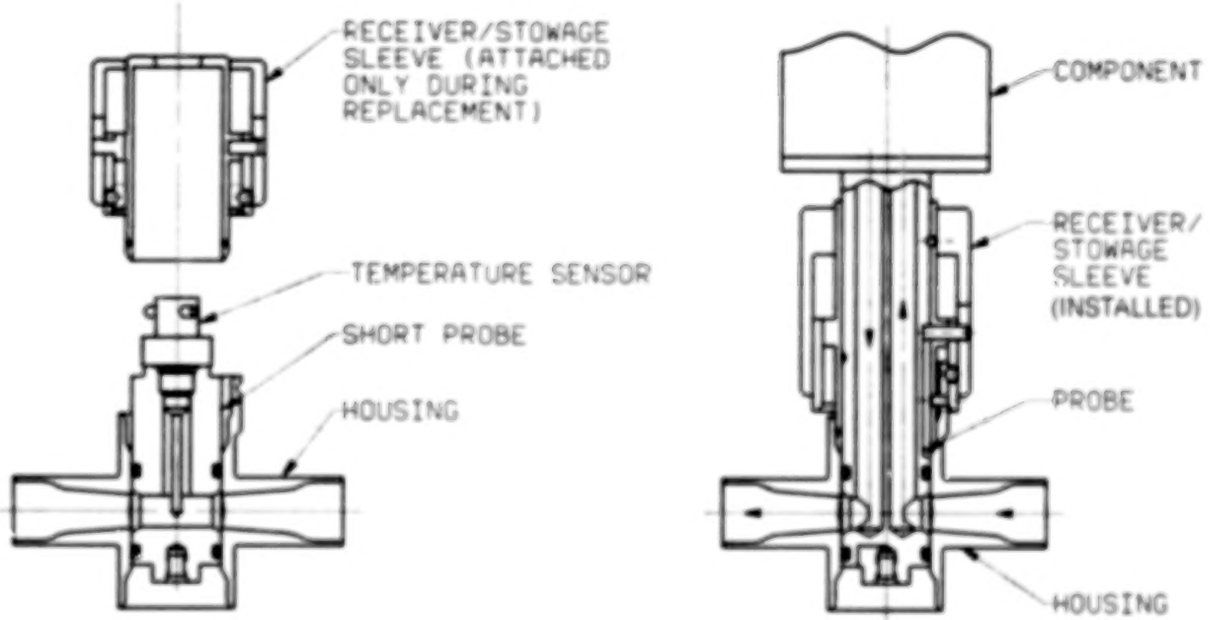


Figure 5

For components which are too large to fit within a cartridge, but too small to require a pair of MMOV's, a variation of the cartridge concept called a probe can be used. Two of the key probe configurations are shown in Figure 6. Short probes are utilized for sensors and other small components which require access on one end and have a diameter which is smaller than that of the cartridge. Long probes are typically used for small to medium sized components such as regulators, pumps, or accumulators whose diameter is larger than that of the cartridge or require access on more than one surface. The probes are replaced in the same way as a valve cartridge, the only difference being that the receiver sleeve is built onto the long probe.

KEY PROBE CONFIGURATIONS



SHORT PROBE (WITH SENSOR)

LONG PROBE

Figure 6

An additional use for probes was conceived that eliminates the need for additional valve porting and immediate line repair in the event that it becomes necessary to continue the operation of a system containing a failed line. A set of probes interconnected by a flex hose can be inserted in the appropriately located housings to bypass the failed line. One end of this bypass configuration is shown in Figure 7.

FAILED-LINE BYPASS PROBE

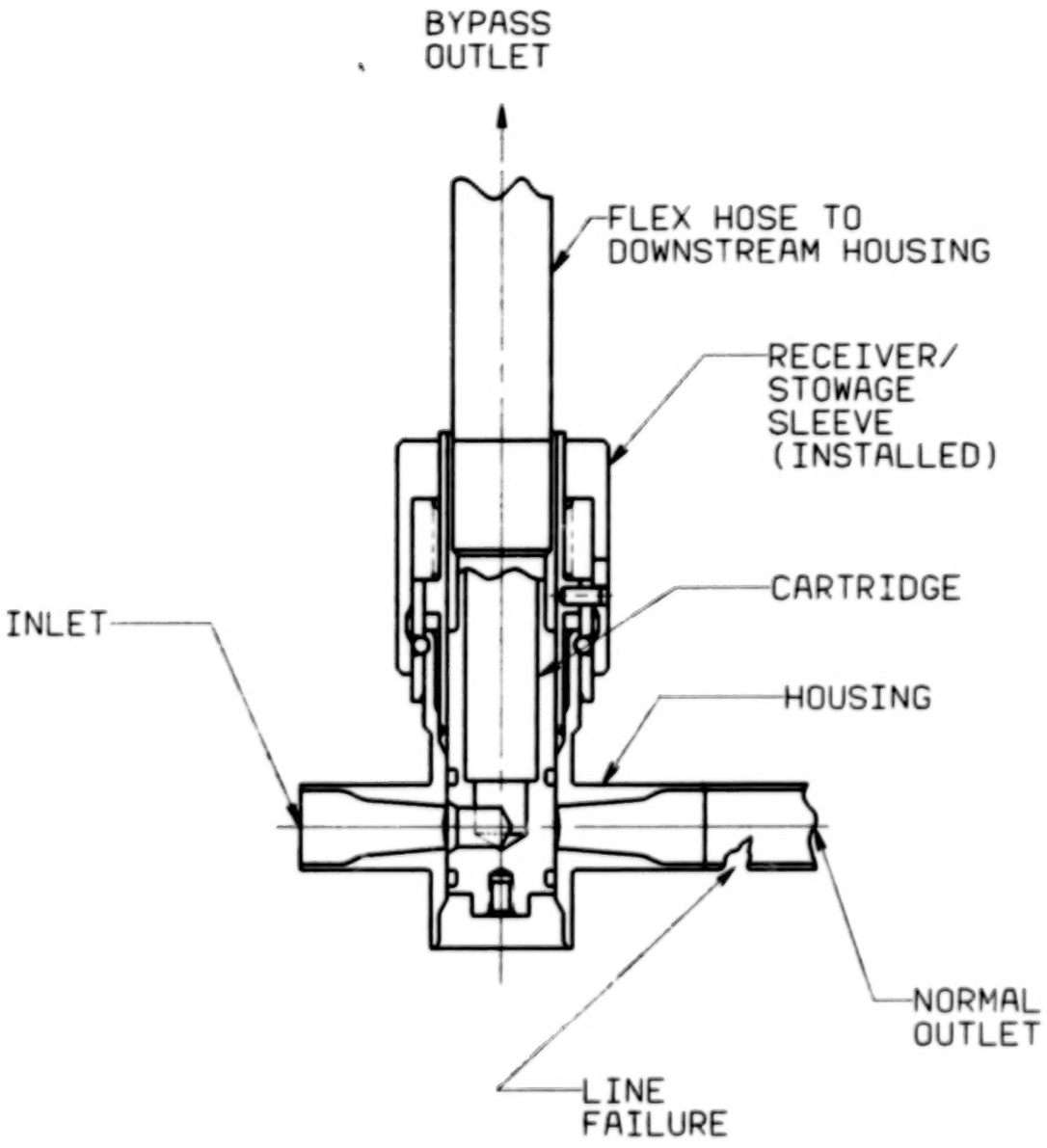


Figure 7

C-3

The cartridge/probe concept allows for a large variety of maintainable hardware. By selecting one version from each column shown in Table 2, one can create as many as 7680 different theoretically possible maintainable assemblies/components. In actuality the realistic number will be between 100 and 200.

All of these applications share the identical MMDV push-pull cartridge replacement concept with all seals and dynamic parts replaceable without liquid line drainage or even depressurization.

MULTIPLE ASSEMBLY COMBINATIONS

HOUSING	CARTRIDGE	OR PROBE	ACTUATOR	COMPONENT
		(ALL WITH COMPONENT)		
1-WAY	2-WAY	1-WAY	90°	
2-WAY	3-WAY	2-WAY	180°	
3-WAY		3-WAY	270°	
4-WAY		4-WAY	360°	AS REQD
L.S.MMDV		FLOATING	ADJUSTABLE	
C.S.MMDV		TELE-SCOPING	90°	
	WITH OR W/O EXPANSION ACCUMULATOR			
	WITH OR W/O COMPONENT	SHORT OR LONG		
5/8" OR 1 1/4"			MANUAL OR ELECTRICAL	
12	64		10	TOTAL OPTIONS

L.S. = LINE SIDE
C.S. = COMPONENT SIDE

Table 2

To keep the impact (i.e., volume, weight, spillage, maintenance time, cost, etc.) at a minimum, Table 3 shows the preferred maintenance scheme for all applications requiring positive isolation.

ISOLATION TECHNIQUE PREFERENCE

Choice	Maintenance Concept	Main Application
1st	Cartridge	Small item which fits into the MMDV cartridge
2nd	Short Probe	Small or electrical items having a diameter smaller than the MMDV housing bore
3rd	Long Probe	Small-to medium-sized component or those requiring multi-sided access
Last	Maintenance Disconnect	Large, high flow rate components or subassemblies

Table 3

ORU Level

An on-orbit replaceable unit (ORU) is defined as an item or group of items that can be automatically fault isolated and safely replaced on-orbit. The selected ORU maintenance level can range from replacement of a piece/part (washers, springs, bearings, seals, etc.) through components or component groups, to a level where the entire subsystem or package is replaced. Each possible ORU level has various advantages and disadvantages.

Hamilton Standard has conducted studies on ECLSS subsystems to determine the optimum ORU level based on weight, volume, and cost considerations. The general results have followed a typical pattern which is illustrated by Figure 8A. The pattern is basically the same for both weight and volume and it indicates that a low level of component grouping or the component level itself is the preferred ORU level, based on a 20-year life cycle. Of course, individual limited life or expendable items should always be ORU's. In general, the installed weight and volume penalty to incorporate direct access to the piece part ORU level is so large as to be impractical and therefore was not considered in the studies.

As opposed to weight and volume, the cost analysis shown in Figure 8B indicates that the group level of maintenance is best but the component level additional impact is quite small. Yet, in order to allow for technology advances, the major functional or subsystem level should also be an ORU. Thus, it is felt that a combination of levels is appropriate for the final selection.

OPTIMUM ORU LEVELS

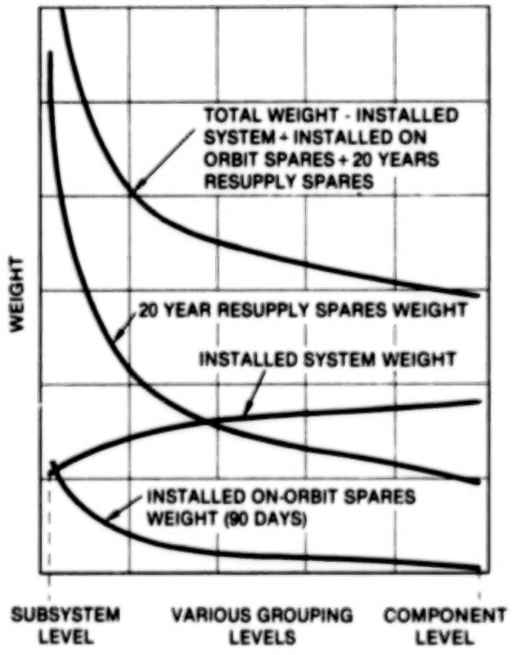

TOTAL WEIGHT - INSTALLED SYSTEM + INSTALLED ON ORBIT SPARES + 20 YEARS RESUPPLY SPARES
20 YEAR RESUPPLY SPARES WEIGHT
INSTALLED SYSTEM WEIGHT
INSTALLED ON-ORBIT SPARES WEIGHT (90 DAYS)
WEIGHT
SUBSYSTEM LEVEL
VARIOUS GROUPING LEVELS
COMPONENT LEVEL

Figure 8A

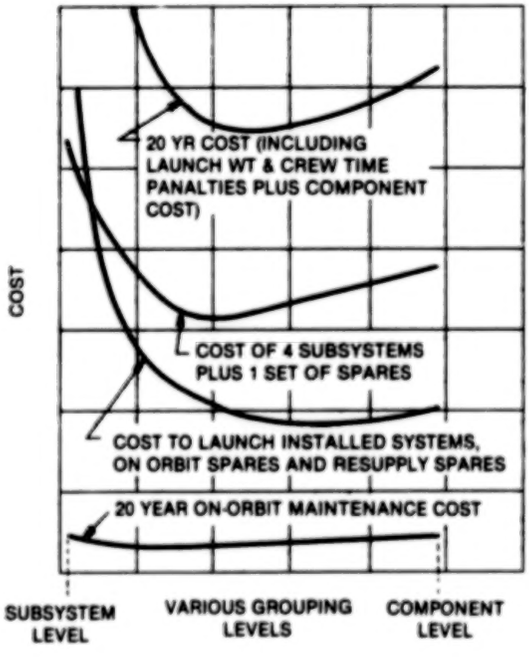

20 YR COST (INCLUDING LAUNCH WT & CREW TIME PANALTIES PLUS COMPONENT COST)
COST OF 4 SUBSYSTEMS PLUS 1 SET OF SPARES
COST TO LAUNCH INSTALLED SYSTEMS, ON ORBIT SPARES AND RESUPPLY SPARES
20 YEAR ON-ORBIT MAINTENANCE COST
COST
SUBSYSTEM LEVEL
VARIOUS GROUPING LEVELS
COMPONENT LEVEL

Figure 8B

Figure 8 assumes that we meet all of the present Space Station maintenance rules. The key ones being:

- An automatic fault detection system must exist and be capable of determining the failed ORU requiring replacement.

- The system must allow for safe direct access to the ORU requiring replacement.

As one goes to lower level ORU's these rules lead to the addition of many sensors and isolation valves in the system, increasing the weight, volume, and cost. These added items can also fail and thus require their own maintenance access. Therefore, the component level of ORU maintenance is not as advantageous as it could be if one would allow more crew intervention to help determine which ORU requires replacement and, when practical, accept the removal of some ORU's in order to get to other more reliable ORU's. It may also be possible to remove and "drain" non-hazardous liquids from the groups of ORU's prior to performing maintenance on the now readily accessible and drained, failed, lower level ORU's themselves. A unit similar to the urinal could be used for this purpose. With this approach, only the group level would possibly need positive isolation features; each lower level ORU within the group would not. These alternate ideas may add some crew time to specific maintenance operations but the reduction in system complexity, cost, weight, and volume, along with the increased reliability, may well prove to be an overall advantage.

Testing Recommendations

Without flight evaluation of the maintenance features, the determination of the conditions requiring positive liquid isolation, and the ability of man to aid in both the fault detection and performance of sub-ORU level maintenance in zero-g, it is very likely that the proper ORU level will not be selected in all cases. This could also result in the incorporation of too many unnecessary isolation features, adding excessive weight, volume, and cost. It is also quite likely that several necessary maintenance features will be missing, causing potential maintenance problems, delays, or even safety hazards.

We believe that the key maintenance issues need both neutral buoyancy and flight evaluation prior to the design of the Space Station itself. We must know and understand all of the issues so we will be able to make the best maintenance decisions for each use. We must know which actions are acceptable to the crew and which are not. Limits for IVA-versus-EVA maintenance must be determined. We must also use flight evaluations to determine the specific needs and requirements of the equipment to be maintained as well as the work station and tools required to perform the maintenance.

Underwater neutral buoyancy tests will allow for evaluation of many of the maintenance features such as slides, guides, latches, fasteners, and accessibility requirements; however, the evaluation of the various liquid isolation and control concepts must be performed in zero-g.

Potential flight application problems have been assessed and recommendations made for a zero-g flight experiment to evaluate key Space Station liquid maintenance issues, including liquid isolation, liquid filling and draining, liquid item replacement, and the repair of failed lines. Figure 9 illustrates the recommended schematic.

FLIGHT ASSESSMENT SCHEMATIC

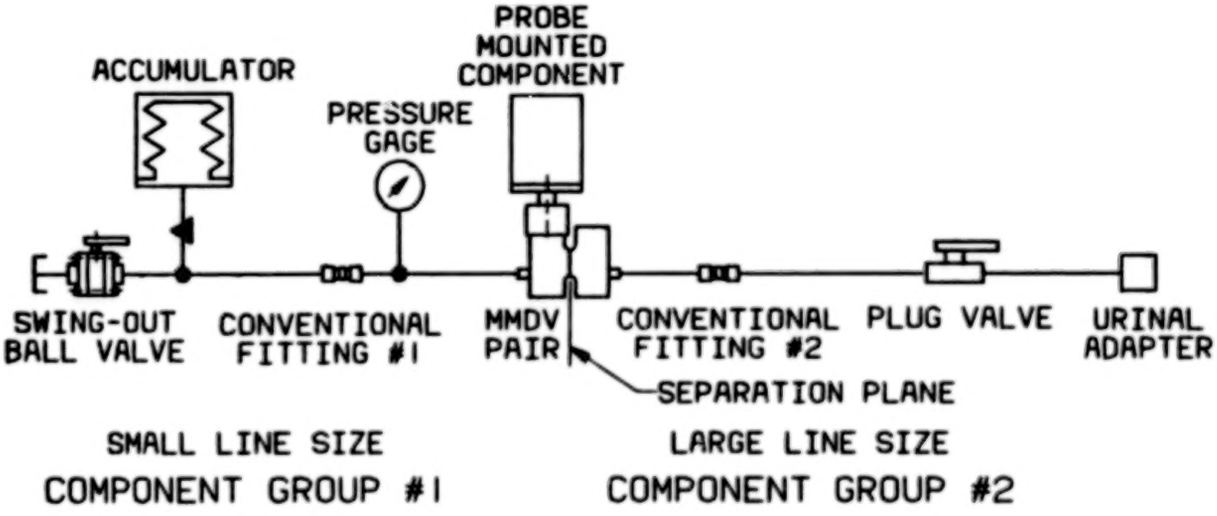


Figure 9

FLIGHT EXPERIMENT OBJECTIVES

- o Need for Positive Isolation - When is positive isolation required? What should be the selection criteria for the separation/isolation feature? Does the direction or speed of interface separation affect the surface tension containment of the liquid? Does the fitting style, line size, or surface coating make any significant difference? Are there any mechanical problems with assembly/disassembly of the fittings and disconnects in zero-g?

- o MMDV Evaluation - Of primary interest is the behavior of the trapped fluid between the MMDV pair. Surface tension in zero-g will tend to hold the majority of this fluid within the valve. Depending upon the test results, a surface tension device such as multiported insert or hydrophilic screen may be required at the valve interfaces. In addition, replacement of the valve cartridge is also recommended in order to assure the acceptability of this operation in zero-g.

- o Probe Evaluation - Insertion and removal of a probe is also recommended, and it is a necessary step for the tests below.

- o Fluid Draining and Charging - The capability of liquid drain and charge on-orbit would have a significant impact on the selected ORU levels and thus the hardware launch weight, volume, and cost. Significant reductions in these areas may be possible by reducing the required number of fluid isolation and thermal expansion features in a group of components and eliminating the need to launch precharged replacements as well as store and return charged items. Also, grouping the components allows for higher packaging densities but increases the requirements for the work station.

- o Permanent Repair of Failed Lines - Concepts, including local freezing, cutting, bonding, welding, brazing, addition of fittings, etc., need to be developed and evaluated.

Table 4

SUMMARY

- o There will be a need for assembly and maintenance of liquid-containing systems and items during the life of the Space Station.

- o Many line separation/isolation schemes exist but most are unproven in zero-g applications. Some may be inadequate for specific applications (hazardous or high pressure liquids) and others may cause excessive cost, weight, and volume impact for relatively for simple applications.

- o A flight experiment evaluation of the key separation/isolation and tubing repair concepts, the tools, work bench facility and access space as well as maintenance times required should be performed prior to the Space Station design phase so the resulting flight hardware will be properly maintainable.

References

1. N. C. Willis, Jr., et. al.: System Features of a Space Station Prototype Environmental Thermal Control and Life Support System. ASME Paper No. 71-AV-22.

2. R. P. Reysa, et. al.: Test Evaluation of Space Station ECLSS Maintenance Concepts. ASME Paper No. 78-ENAs-43.

3. T. E. Burr, et. al.: Maintainable Maintenance Disconnect Valve (MMDV) for On-Orbit Component Replacement. ASME Paper No. 80-ENAs-42.

4. John B. Greene, Jr., et. al.: Maintenance Components for Space Station Long Life Fluid Systems. ASME Paper No. 861005.

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SPACE EXPERIMENT DEVELOPMENT PROCESS

James F. DePauw
NASA Lewis Research Center
Cleveland, Ohio

This paper describes a process for developing space experiments that utilize the Shuttle. The role of the Principal Investigator is described as well as the Principal Investigator's relation with the project development team.

The paper describes the sequence of events from an early definition phase through the steps of hardware development. The major interactions between the hardware development program and the Shuttle integration and safety activities are also shown. Some lessons learned are listed along with references of potential value to experimenters lacking Shuttle experience.

The presentation is directed to people with limited Shuttle experiment experience. The objective is to summarize the development process, discuss the roles of major participants, and list some lessons learned in our short experience. Two points should be made at the outset. First, no two projects are the same so the process varies from case to case. I only hope to convey some principles here to help you find your way through the "system." Second, my recent experience has been mostly with Code EN/Microgravity Science and Applications Division (MSAD). This presentation is heavily influenced by the system evolving there.

OVERVIEW

- INTRODUCTION
- ORGANIZATIONAL ELEMENTS
- PRINCIPAL INVESTIGATOR ROLE
- DEVELOPMENT ROLE
- DEVELOPMENT APPROACHES
- FLOW CHART AND MILESTONES
- LESSONS LEARNED
- REFERENCES

Figure 1

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INTRODUCTION

- MANY CATEGORIES EXIST FOR SPACE EXPERIMENTS
  - SCIENCE VS. TECHNOLOGY
  - LARGE VS. SMALL
  - CARRIERS AND LOCATIONS
    - MIDDECK LOCKERS/CABIN ENVIRONMENT
    - MPESS/BAY ENVIRONMENT
    - GAS CANS
    - SPACELAB
    - SPACELAB PALLET
    - ETC.
- DIFFERENT SPONSORS USE DIFFERENT PROCESSES
- MOST EXPERIMENTS ARE COSTLY
- MOST ARE LONG-TIME COMMITMENTS

Figure 2

This introductory slide enumerates some of the variables that a space experiment developer encounters. This is compounded by system and personnel changes that occur at different organizations over the life of a project. It is understandable that each project proceeds through the system differently. On the positive side, there is much documentation available. Many precedents and good examples exist. The fact that many experiments have flown provides assurance that it is possible to succeed.

ORGANIZATIONAL ELEMENTS

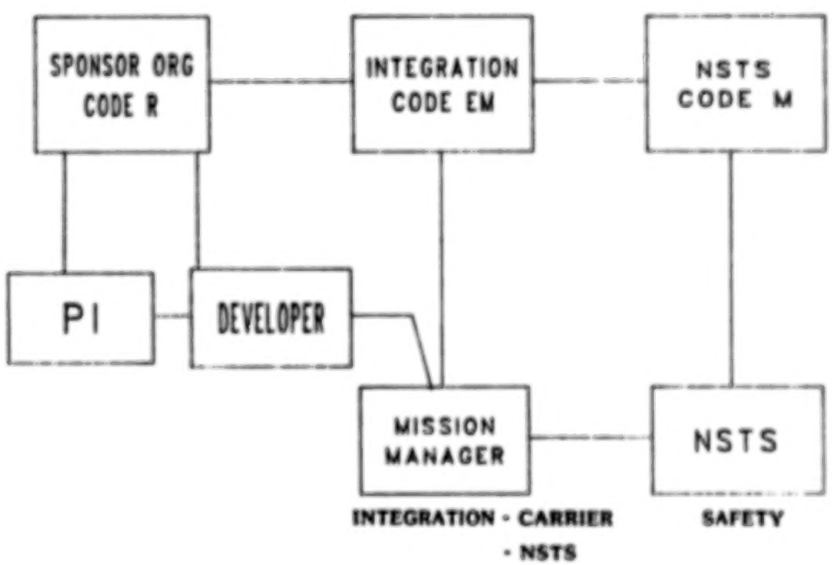

Figure 3

The major organizational elements for an OAST experiment are shown. This should be viewed as a theoretical model. In practice, much informal networking among various elements is needed to accomplish the project.

Headquarters organizations are shown on the top tier. The sponsoring organization usually funds the Principal Investigator (PI) activity separately from the project development activity so the autonomy of each can be preserved. Integration of the experiment into the National Space Transportation System (NSTS) has usually been delegated by Code R to Code EM. They, in turn, fund a mission manager and supporting organization at the Johnson Space Center (JSC), Marshall Space Flight Center (MSFC), or Goddard Space Flight Center (GSFC), to integrate the experiment with the carrier, other experiments, and other elements of the NSTS. Eventually, interaction with the Shuttle operators of Code M and their supporting Centers is required.

PI ROLE AND ACTIVITIES

- RESPONSIBLE FOR THE EXPERIMENTAL IDEA
- EXPLORE IDEA VIA ANALYSIS
- DEMONSTRATE CONCEPT VIA GROUND TEST
- JUSTIFY THE NEED FOR SPACE TEST
- DEFEND THE EXPERIMENT IN REQUIRED "PEER" REVIEWS
- GENERATE REQUIREMENTS DOCUMENT AND EDUCATE DEVELOPERS
- PRESENT EXPERIMENT AT REQUIREMENTS REVIEW
- MONITOR DEVELOPMENT TO INSURE TECHNICAL INTEGRITY
- ANALYZE AND REPORT RESULTS

Figure 4

The Principal Investigator is usually the prime mover for the endeavor. He conceives the idea. He explains it, defends it, and watches over it until the end when he evaluates results and publishes the findings. Some of the principal PI activities are listed.

The task of specifying requirements is always a sensitive one. The PI typically desires state-of-the-art measurements and accommodations to get the best experiment. These requirements drive cost and schedule and in general, affect the ability to develop the system. It is important for the PI and the development team to agree early on appropriate requirements.

DEVELOPMENT ROLE AND ACTIVITIES

- O ITERATE REQUIREMENTS WITH P.I.
- O DEVELOP PROJECT PLAN (COST, SCHEDULE, ETC.)
- O DEVELOP FLIGHT HARDWARE TO MEET REQUIREMENTS
- O KEEP P.I. UP-TO-DATE ON PROGRESS AND PROBLEMS
- O CONDUCT MISSION OPERATIONS
- O COORDINATE MISSION INTEGRATION, SAFETY, MANIFESTING, ETC.

Figure 5

Though the PI, in most cases, is very capable, he may not have the skills, organization, or the desire to develop and integrate the hardware with the space transportation system. That is the contribution of the development organization whose activities are summarized on this slide.

DEVELOPMENT APPROACH OPTIONS

- O USE OR MODIFY EXISTING FACILITY
- O DEVELOP NEW HARDWARE
  - PI TAKES FULL RESPONSIBILITY
    - EXECUTES LITTLE TO MOST OF PROGRAM
    - CONTRACTS FOR REMAINDER
  - PI TAKES SCIENTIFIC RESPONSIBILITY ONLY
    - LETS ANOTHER SOURCE SUPPLY HARDWARE

Figure 6

There are several options for approaching the development of the experiment. A simple approach is to develop an experiment that uses an existing facility. That could give the PI team instant access to an experienced support staff that could carry out the experiment quickly and efficiently. However, that approach constrains the team.

A more comprehensive experiment may require that new hardware be developed. The PI can develop as little or as much as his situation dictates.

SPACE EXPERIMENT DEVELOPMENT MILESTONES

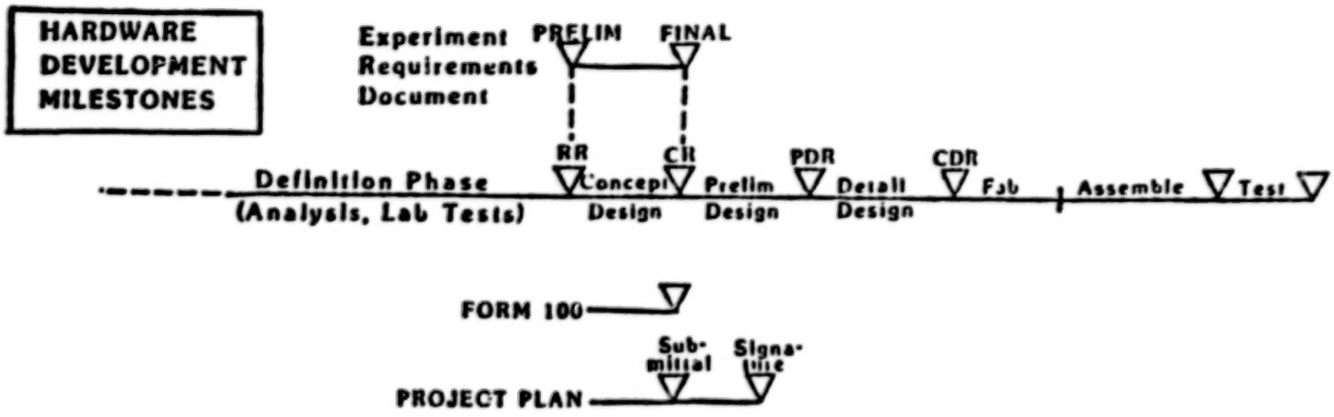

Figure 7

The process starts with a definition phase containing the analysis, breadboarding, and ground testing that spawns the experiment. When the idea is thought to be viable, the PI documents the experiment background, objectives, justification, and engineering requirements so that an engineering team can generate flight hardware design concepts.

A list of the critical technology issues to be addressed in the concept design phase of the program is useful. Cost and schedule information is needed on (a) the concept design phase of the program and (b) the total program. The estimate for (a) will, of course, be more accurate than the estimate for (b). The culmination of this effort is a Requirements Review (RR) involving the PI and hardware development organizations, the sponsoring organization, and any reviewers deemed appropriate.

If the RR is successful and funding is obtained, the project group continues with the conceptual design. Enough engineering should be done in the concept design phase so that an assessment of the feasiblility can be made. The key science and development issues should be demonstrated by test or analysis, thus providing a sound foundation upon which to base a project.

During the concept design phase, the Experiment Requirements Document is negotiated and refined between the PI and engineering organizations so that at the Concept Review (CR), a mutually acceptable document is available.

NOTE: In the Code EN program, RR and CR are called Conceptual Design Review (CoDR) and Preliminary Requirements Review (PRR), respectively.

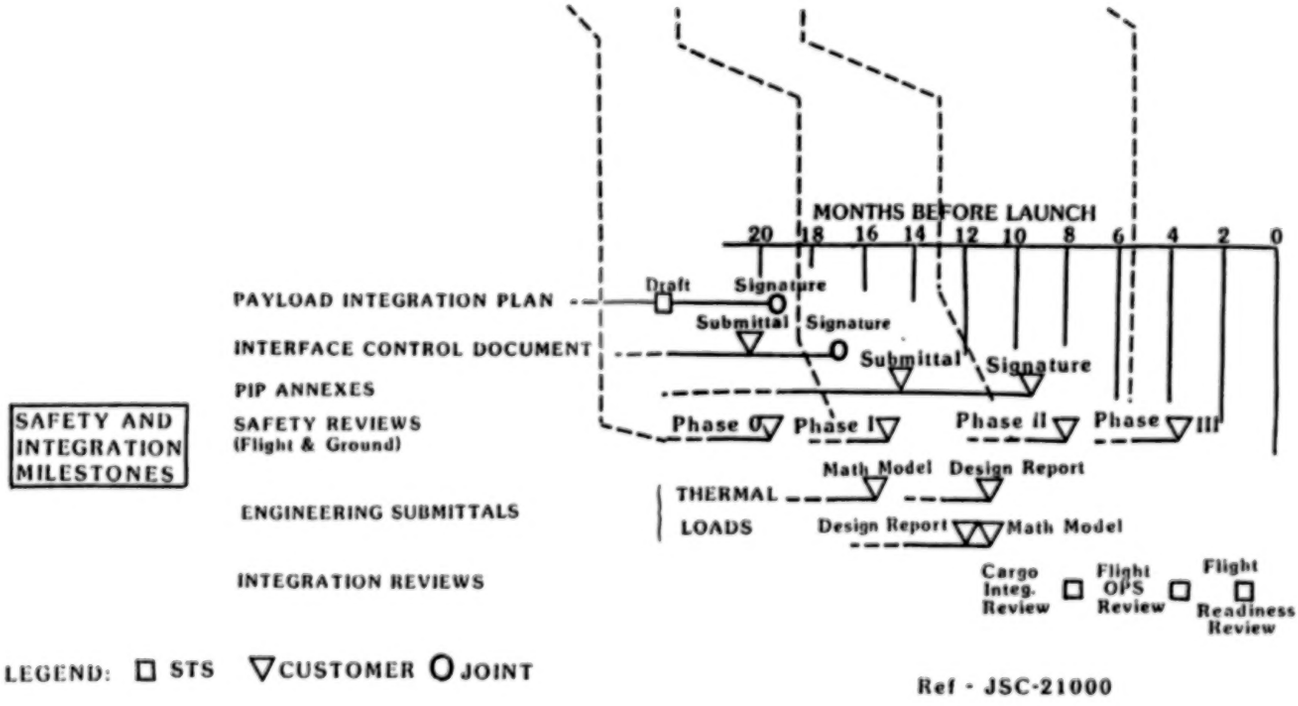

Figure 8A

The Form 100 is necessary to obtain NSTS organization support; it should be processed and signed as the conceptual design takes shape. The Project Office submits a draft to Headquarters which then arranges needed support.

As you complete the conceptual design, submit a cost and schedule estimate for the entire project as part of a project plan. The project plan is an important agreement between the sponsor and the project organization that documents funding, schedule, and other critical project specifics.

Succeeding development activities are shown along the development line. The CR is followed by a design phase leading to a Preliminary Design Review that will enable approval to proceed with detailed design. The Critical Design Review culminates with the approval to fabricate hardware, etc. The typical hardware development milestones are shown in relative to the NSTS integration and safety reviews.

(Note that the scale for NSTS milestones does not apply to the hardware development milestones.)

SPACE EXPERIMENT DEVELOPMENT MILESTONES

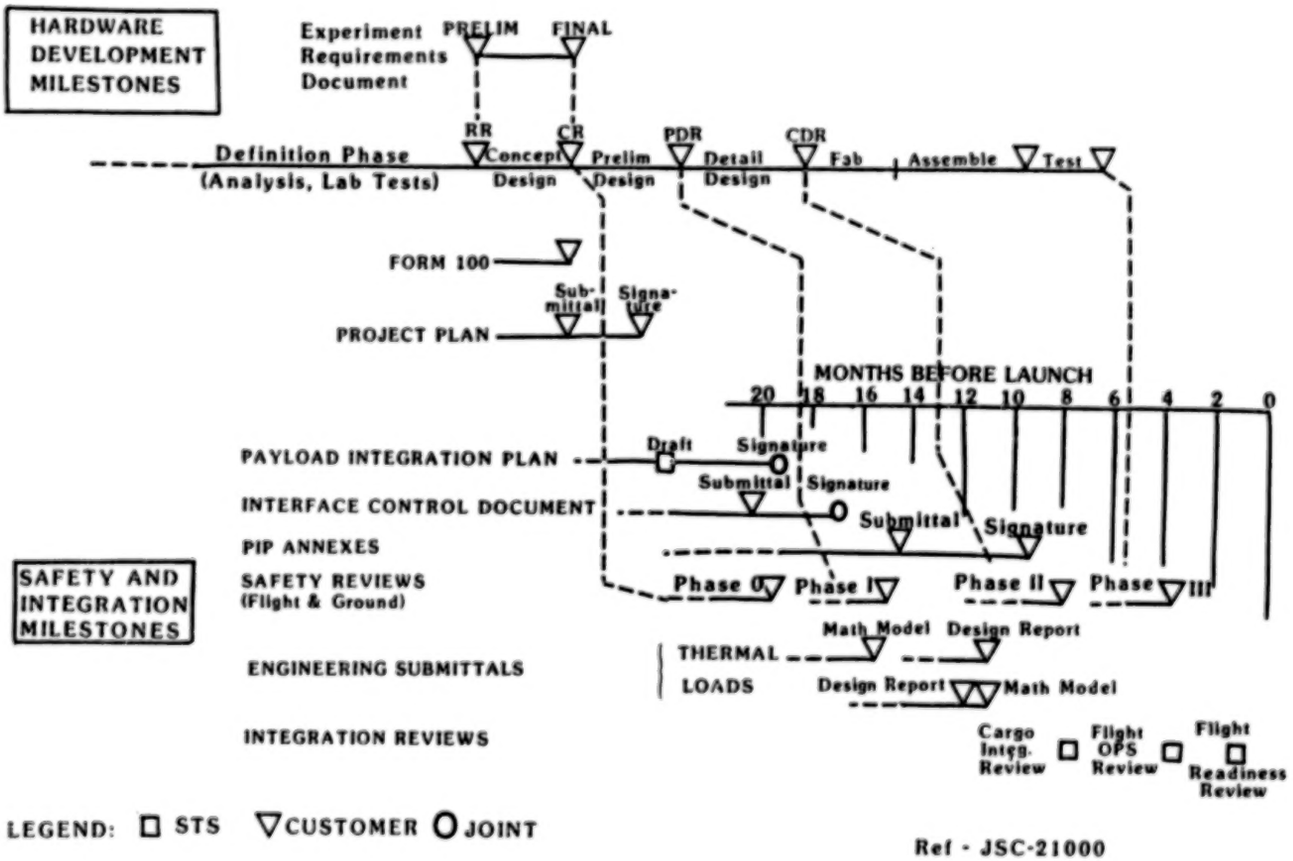

Figure 8B

We at Lewis have some history of space experiments and launch vehicle accomplishments. We are relative newcomers to Shuttle experiment development. In spite of that, we have learned some lessons that may be useful.

The P.I. and the development teams must develop mutual understanding to resolve differences promptly and amiably in order to keep the program on a single, focused path.

Documentation and interpretations are sometimes inconsistent; therefore, investigators must be thorough in exploring questionable areas with NSTS personnel.

Thorough testing at the highest system-level practical can add confidence of success. Such testing can also compensate for shortcuts taken at parts, components, and subsystem levels.

LESSONS LEARNED

- KEEP THINGS SIMPLE
- REVIEWS TEND TO IMPROVE BUT COMPLICATE THE EXPERIMENT CONCEPT
- P.I. AND DEVELOPER MUST DEVELOP MUTUAL UNDERSTANDING
- PROJECTS ARE LONG AND COSTLY
  (A GENUINELY INTERESTED CORE GROUP IS NEEDED)
- DOCUMENTATION (AND INTERPRETATION) IS SOMETIMES INCONSISTENT
- SOFTWARE DEVELOPMENT MUST BE MONITORED CLOSELY
- THOROUGH SYSTEM-LEVEL TESTING INCREASES PROBABILITY OF SUCCESS

Figure 9

There is an awesome amount of documentation available to guide experiment developers. I have listed only a few that could provide a starting place for the newcomer. The references are available from the following sources:

1. MSFC Spacelab Payload Project Office, Code JA11,
   Telephone (205) 453-2430.

2. JSC Customer Service Center, Mail Code TC12,
   Telephone (713) 483-2337.

3. Available from the authors.

A list of key documents from reference 1 is included in this handout along with appendix A of reference 2. The lists identify some of the available documentation.

REFERENCES

1. STS INVESTIGATOR'S GUIDE - MSFC (205) 453-2430

2. SHUTTLE/PAYLOAD INTEGRATION ACTIVITIES PLAN (JSC-21000-IAP) (713) 483-2337

3. FLYING A SCIENTIFIC EXPERIMENT ABOARD THE SPACE SHUTTLE - A PERSPECTIVE FROM THE VIEWPOINT OF THE EXPERIMENTER BY WARREN D. HYPES, NASA LANGLEY AND JOSEPH C. CASAS, OLD DOMINION UNIVERSITY RESEARCH FOUNDATION

Appendix A

Referenced Documents List

Copies of the documents listed below may be obtained by mail or telephone request from:

Customer Service Center
Mail Code TC12
NASA Lyndon B. Johnson Space Center
Houston, TX 77058

713-483-2337

Standard Integration Plans

Standard Integration Plan for Payloads Using Small Payload Accommodations, JSC-21000-SIP-SML

Shuttle/Payload Standard Integration Plan for Spacelab Payload (Generic), JSC-21001-SIP-SLB

Standard Integration Plan for Payloads Using Standard Accommodations (Deployable), JSC-21002-SIP-DEP

Standard Integration Plan for Payloads Using Middeck-Type Payload Accommodations, JSC-21003-SIP-MDK

Standard Integration Plan for Payloads Using Standard Accommodations (Attached), JSC-21004-SIP-ATT

Shuttle/Payload Standard Integration Plan for Payload Specialist Payloads, JSC-21005-SIP-PSP

Shuttle/Payload Standard Integration Plan for DOD Deployable/Retrievable-Type Payloads, JSC-21006-SIP-DOD

Interface Definition Documents

Shuttle/Payload Interface Definition Document for Small Payload Accommodations, JSC-21000-IDD-SML

Shuttle/Payload Interface Definition Document for Middeck Payload Accommodations, JSC-21003-IDD-MDK

Shuttle/Payload Interface Definition Document for Standard Accommodations, JSC-21004-IDD-STD

Miscellaneous Documents

Space Transportation System Customer Accommodations Document, JSC-21000-HBK

Shuttle EVA Description and Design Criteria, JSC-10615

KSC Launch Site Accommodations Handbook for STS Payloads, K-STSM-14.1

Space Transportation System Reimbursement Guide, JSC-11802

NSTS Optional Services Pricing Manual, JSC-20109

Payload Operations Control Center Capabilities Document, JSC-14433

Safety Policy and Requirements for Payloads Using the STS, NHB 1700.7

Implementation Procedures for STS Payloads System Safety Requirements, JSC-13830

Mission Integration Control Board Configuration Management Procedures, JSC-18468

Key Documents & References

Attached Shuttle Payload Carriers
Brochure provided by NASA/GSFC, Greenbelt, MD 20771

Microgravity Science and Applications – Experiment Apparatus and Facilities
Brochure produced by NASA/MSFC Marshall Space Flight Center, AL 35812

Guide to the Life Sciences Flight Experiments Program
Produced by NASA Life Sciences Flight Programs Branch at NASA Headquarters, Washington, DC 20546

User's Guide to Spacelab Payload Processing
Produced by Cargo Projects Office, NASA/KSC, Florida 32899

STS User Handbook
NASA Headquarters, Washington DC 20546

Launch Site Accommodations Handbook for STS Payloads
NASA/KSC Document, K-STSM-14.1

The User's Guide to Spacelab Payload Processing
Brochure provided by NASA/KSC, Florida 32899

Mission Requirements on Facilities/Instruments/ Experiments for STS Attached Payloads (MROFIE)
MSFC JA-447

Payload Flight Equipment Requirements for Safety-Critical Structures
MSFC JA-418

Payload Developer's Guide for Launch Site Operations
KSC IV 0018.0

Spacelab Payload Accommodations Handbook (SPAH)
SLP/2104

Space Shuttle System Payload Accommodations
JSC 07700, Vol. XIV

Safety Policy and Requirements for Payloads Using the STS
NHB 1700.7A

Orbiter Middeck Payload Provisions Handbook
JSC-16536

STS Payload Safety Guidelines Handbook
JSC 11123

POCC Capability Document
JSC-14433

"Flying a Scientific Experiment Aboard the Space Shuttle – A Perspective from the Viewpoint of the Experimenter,"
A Technical Paper by Warren Hypen (NASA/LaRC) and Joseph C. Casas (Old Dominion University Research Foundation, Norfolk, Virginia)

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SHUTTLE GET-AWAY SPECIAL EXPERIMENTS

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McDonnell Douglas Corporation
St. Louis, Missouri

This presentation describes two shuttle Get-Away-Special (GAS) experiments built by McDonnell Douglas to investigate low-g propellant acquisition and gaging. The first experiment, which was built under internal research and development funding, was flown on shuttle mission 41-G in October 1984. The second experiment, which was built under contract to the International Telecommunications Satellite Organization (INTELSAT), has been qualified for flight and is waiting for a flight assignment.

The tests performed to qualify these experiments for flight are described, and the lessons learned which can be applied to future GAS experiments are discussed. Finally, survey results from 134 GAS experiments flown to date are presented. On the basis of these results it is recommended that future GAS experiments be qualified to shuttle thermal and dynamic environments through a rigorous series of mission operating tests. Furthermore, should automatic activation of the experiment be required during the boost phase of the mission, NASA-supplied redundant barometric switches should be employed to trigger the activation.

The two GAS experiments built by McDonnell Douglas are identified below. The first experiment, G074, was flown on shuttle mission 41-G in October 1984. It was designed to investigate the operation of two-surface tension propellant acquisition concepts in low-g, self-filling gallery legs, and a refillable trap. The second experiment, G-522, was built under contract to INTELSAT and was designed to measure the low-g performance of two-propellant gaging concepts, ultrasonic point sensors, and a nucleonic gaging system. These gaging concepts are high value candidates for future geostationary satellites. The G-522 experiment has been qualified for flight and is now waiting for a shuttle flight assignment.

MCDONNELL DOUGLAS GAS EXPERIMENTS

11-6303

EXPERIMENT	DESCRIPTION
G-074	PROPELLANT ACQUISITION • SELF-FILLING GALLERIES • REFILLABLE TRAP
G-522	PROPELLANT GAGING • ULTRASONIC POINT SENSORS • NUCLEONIC GAGING

Figure 1

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Two views of the G074 propellant acquisition experiment are shown in Figure 2. All experiment components were attached to a 6061-T6 aluminum frame structure. The top of the structure was centilevered from a NASA-supplied mounting plate, and the bottom of the structure was supported laterally by four pads which pressed against the walls of the flight canister. The experiment components consisted of a test tank, positive displacement accumulator, valves and plumbing, control electronics, batteries, and a movie camera and lighting system.

The experiment was designed to be activated automatically at launch by redundant acoustic switches. This technique was used successfully on a previous NASA-Goddard GAS experiment. The switches were set to sense acoustic pressure levels at main engine ignition and then trigger the experiment's control and timing circuits.

The experiment weighed 106 pounds and was installed in a 5-cubic-foot GAS canister. A detailed description of the G074 experiment is contained in Reference 1.

G074 EXPERIMENT

11-6294

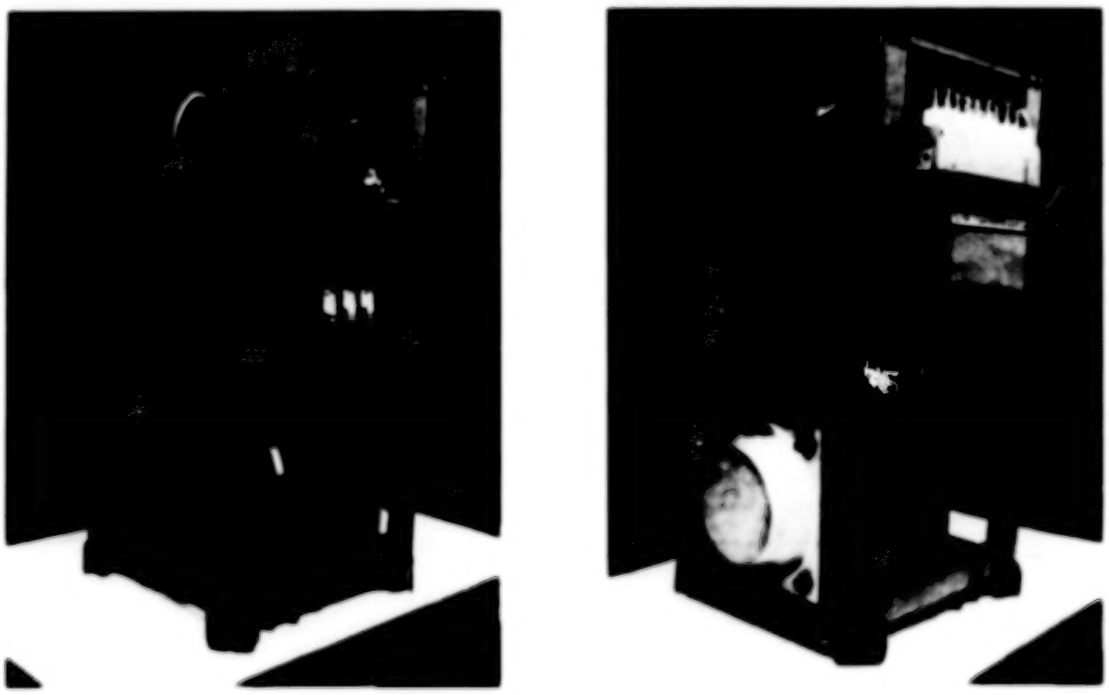

Figure 2

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The test tank (Figure 3) is a bolted assembly consisting of a cylindrical Plexiglas section, an aluminum forward dome, and an aluminum aft end plate. The tank is divided into forward and aft compartments by an internal Plexiglas bulkhead. The three gallery legs in the forward compartment are made of Plexiglas to allow visual (movie) evaluation of gallery filling during zero-g. Each gallery leg has a flat, stainless steel screen surface along its outer face (adjacent to the tank wall) and a vent screen inside the forward vent baffle assembly. Gallery leg dimensions and screen mesh sizes are varied in order to acquire parametric data during the gallery fill process.

The internal bulkhead assembly contains a tapered Plexiglas vent stack to provide an exit passage for entrapped gas during passive fill of the aft trap compartment. The vent stack is covered by two perforated plate discs at its forward end.

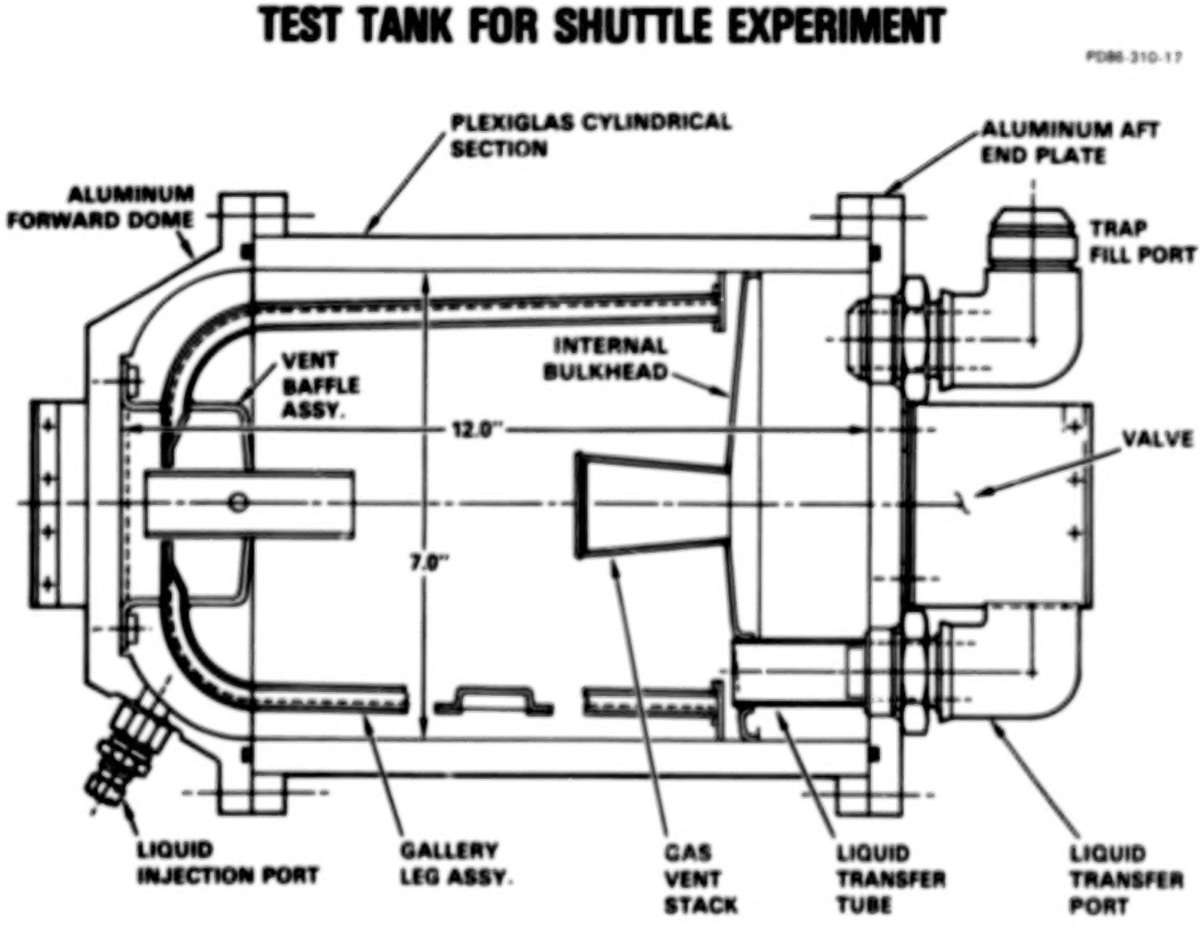

Figure 3

The tank operating sequence is shown in Figure 4. The tank is launched with a partial liquid load (Freon 113) in the forward compartment and a nearly empty aft compartment. During the zero-g interval following main engine cutoff, the three gallery legs fill by capillary pumping. The baffle assembly at the forward end of the tank keeps the gallery vent screens dry until the gallery fill process is complete. The maximum gallery fill time is approximately 10 seconds.

After the first Orbital Maneuvering Subsystem (OMS) burn, additional Freon 113 is injected into the tank forward compartment from an auxiliary positive displacement accumulator in preparation for the trap filling experiment. The trap filling experiment is performed during the second OMS engine firing. The transfer valve at the tank outlet is signalled open to allow liquid flow from the forward to aft compartment. During the burn, gas inside the aft compartment is expelled through the vent stack perforated plates by the hydrostatic pressure imposed across the entrapped gas bubble, allowing the aft compartment to fill. The aft compartment fill rate is retarded by liquid flow pressure losses through the transfer line and valve and by gas flow pressure losses through the vent stack perforated plates. For an OMS acceleration of 0.04 g's, the aft compartment fill time is approximately 30 seconds.

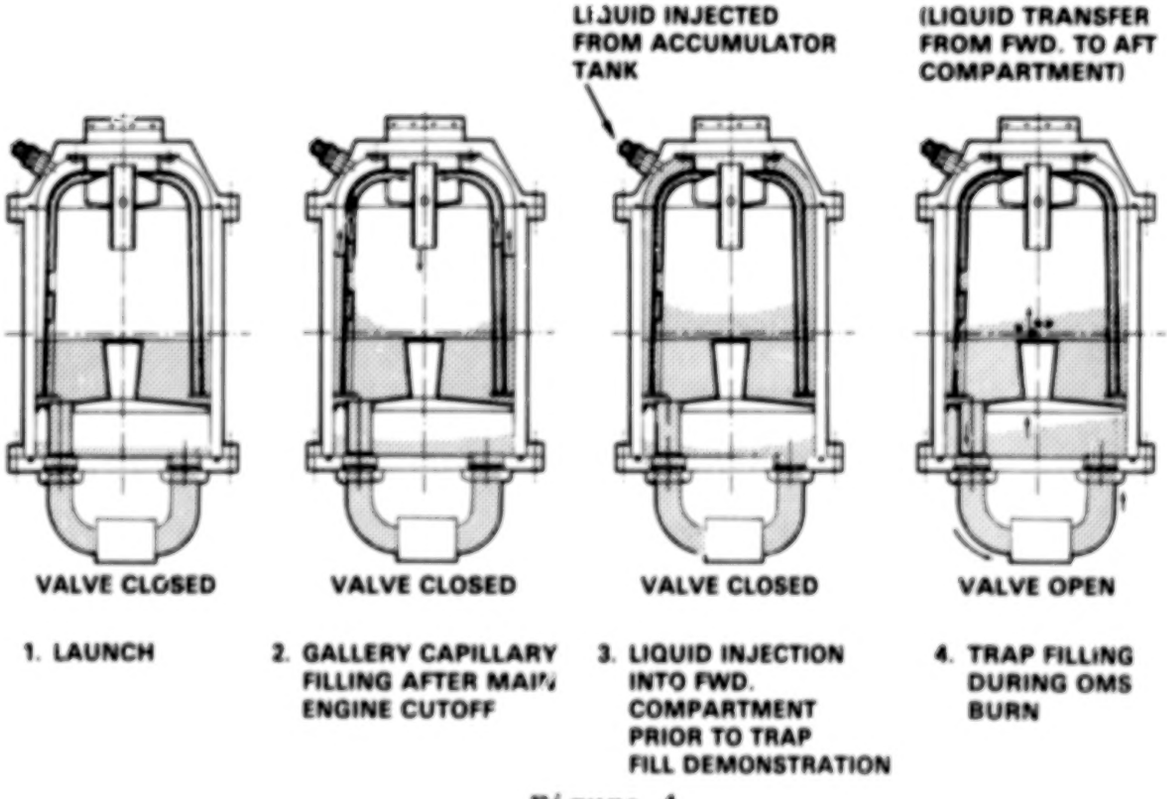
OPERATING SEQUENCE: GO74 EXPERIMENT
PD86-310-16
LIQUID INJECTED FROM ACCUMULATOR TANK
(LIQUID TRANSFER FROM FWD. TO AFT COMPARTMENT)
VALVE CLOSED
VALVE CLOSED
VALVE CLOSED
VALVE OPEN
1. LAUNCH
2. GALLERY CAPILLARY FILLING AFTER MAIN ENGINE CUTOFF
3. LIQUID INJECTION INTO FWD. COMPARTMENT PRIOR TO TRAP FILL DEMONSTRATION
4. TRAP FILLING DURING OMS BURN

Figure 4

Environmental testing was performed to qualify the experiment for flight. The testing consisted of high and low temperature operating tests, vibration tests and acoustic tests.

The high and low temperature tests were performed by installing the fully serviced payload inside an insulated thermal enclosure. Conditioned air at 65°C or nitrogen at -28°C was circulated through the enclosure to bring the payload to equilibrium. The payload was activated, and an entire mission sequence was run while maintaining the equlibrium temperature.

The vibration tests were performed with the fully serviced payload installed in a NASA shipping cylinder to simulate the flight canister. The imposed vibration spectrum (6 g_{RMS} - overall) was in accordance with the NASA flight specification for GAS payloads. Tests were performed in each of three axes (2 lateral and 1 vertical) for 40 seconds per axis.

An acoustic test was performed to verify the operational integrity of the payload following vibration testing. An acoustic environment was imposed which duplicated the sound pressure level and frequency spectrum measured inside the GAS canister on the STS-3 mission at liftoff. The payload was activated successfully with its acoustic switches at a threshold sound pressure level of 110 dB, and an entire mission sequence was run.

FLIGHT CERTIFICATION TESTS: G074 EXPERIMENT

11-6304

- PROOF PRESSURE
- ROOM TEMPERATURE MISSION SEQUENCE
- HIGH TEMPERATURE MISSION SEQUENCE
- LOW TEMPERATURE MISSION SEQUENCE
- VIBRATION TEST
- ACOUSTIC TEST
- ROOM TEMPERATURE MISSION SEQUENCE

Figure 5

The G074 experiment was flown on shuttle mission 41-G in October 1984. A review of the test films revealed that the experiment was activated on the ground, prior to flight. It is believed that the experiment's acoustic switches were triggered by a Delta launch one day after the experiment was installed in its flight canister. The Delta launch pad is adjacent to the GAS payload processing facility, and acoustic levels during a launch are reported to be quite high.

To obtain the desired zero- and low-g data, the experiment was flown in a NASA KC-135 flight test on 5 March 1986. The experiment operated successfully during this flight test and, as such, a second shuttle flight is not planned.

FLIGHT RESULTS: G074 EXPERIMENT

11-6305

- FLOWN ON SHUTTLE MISSION 41G (5 OCT 84)
- EXPERIMENT ACOUSTIC SWITCHES ACTIVATED PREMATURELY BEFORE FLIGHT
- EXPERIMENT COULD NOT BE RESET AND WAS NOT ACTIVATED DURING FLIGHT
- EXPERIMENT OPERATION AT ZERO-& LOW-G VERIFIED ON KC-135 FLIGHT TEST (5 MAR 86)
- SHUTTLE REFLIGHT NOT PLANNED

Figure 6

Based on the G074 flight experience, it is recommended that use of acoustic or "g" switches for experiment activation be avoided. If experiment activation during boost is required, then barometric switches (which sense atmospheric pressure) should be used. Because of the G074 failure, NASA-Goddard is now providing redundant barometric switches as a standard service for GAS payloads.

LESSONS LEARNED: G074 EXPERIMENT

11-6306

- AVOID USE OF ACOUSTIC OR "G" SWITCHES TO ACTIVATE EXPERIMENT DURING BOOST
- IF EXPERIMENT ACTIVATION DURING BOOST IS REQUIRED, USE BAROMETRIC SWITCHES
- BECAUSE OF G074 FAILURE, NASA-GODDARD IS NOW PROVIDING REDUNDANT BAROMETRIC SWITCHES AS STANDARD SERVICE FOR GAS PAYLOADS

Figure 7

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The purpose of the G522 experiment (Figure 8) is to provide an orbital test of ultrasonic point sensor and nucleonic gaging systems. The experiment consists of the following elements:

- Plexiglas test tank with ultrasonic and nucleonic gaging systems
- Two-liquid supply (positive displacement) accumulators with associated valving and plumbing
- Support structure
- Power supply
- Control electronics and data acquisition system
- Movie camera and lighting

The overall experiment weighs 145 pounds and will be contained within a standard 5-cubic-foot GAS canister. The canister will be purged and pressurized with dry nitrogen gas to 14.7 pounds/square inch-absolute prior to installation into the Orbiter.

A complete description of the experiment is contained in Reference 2.

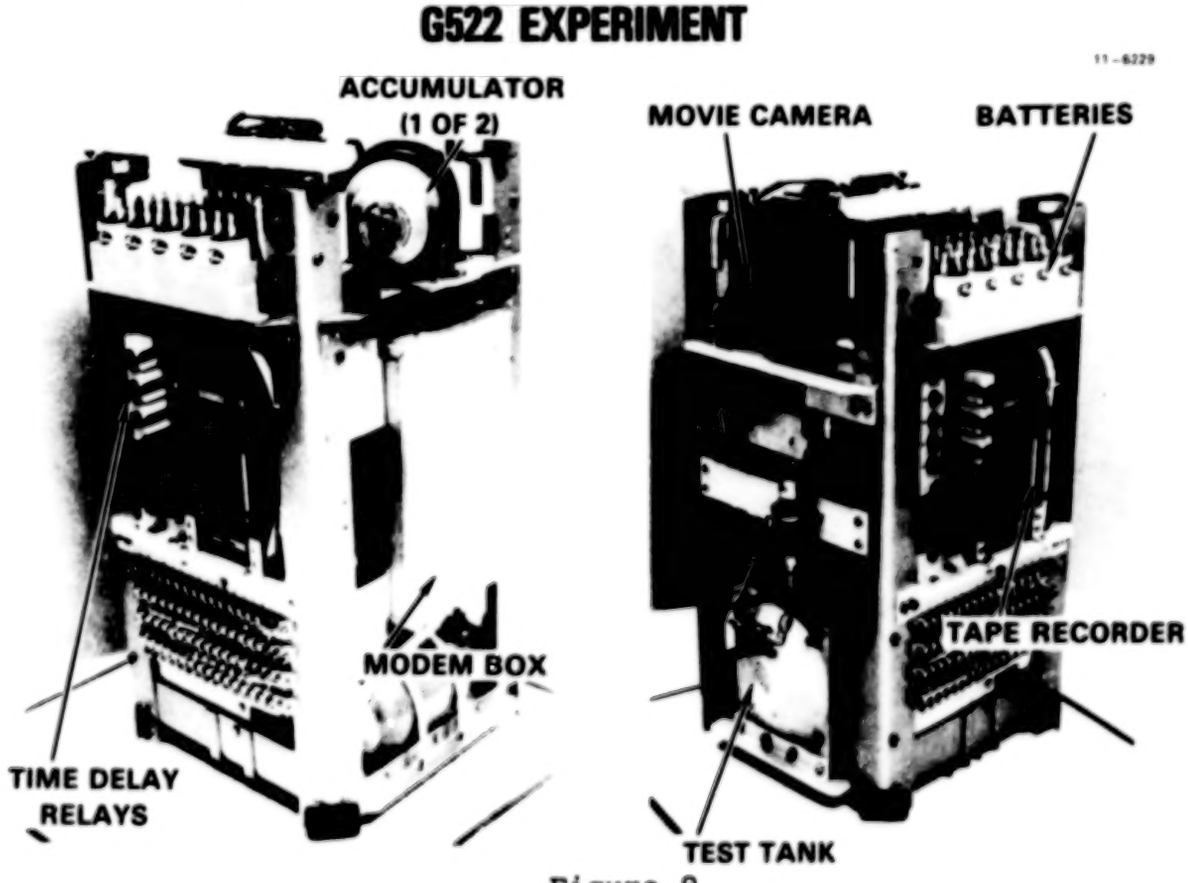

Figure 8

In order to permit packaging all required equipment within the 5-cubic-foot GAS canister, a small 5.75 by 8 inch tank was selected having an internal shape simulating a cylindrical propellant tank with ellipsoidal end domes.

As shown in Figure 9, the tank is a bolted assembly consisting of a cylindrical Plexiglas section, internal vane device for liquid positioning, and aluminum end domes. The Plexiglas section is sealed against the end domes with rubber O-rings. The internal vane device consists of four radial vanes that position the test liquid (Freon 113) in a wall-bound orientation in zero-g.

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TEST TANK: G522 EXPERIMENT

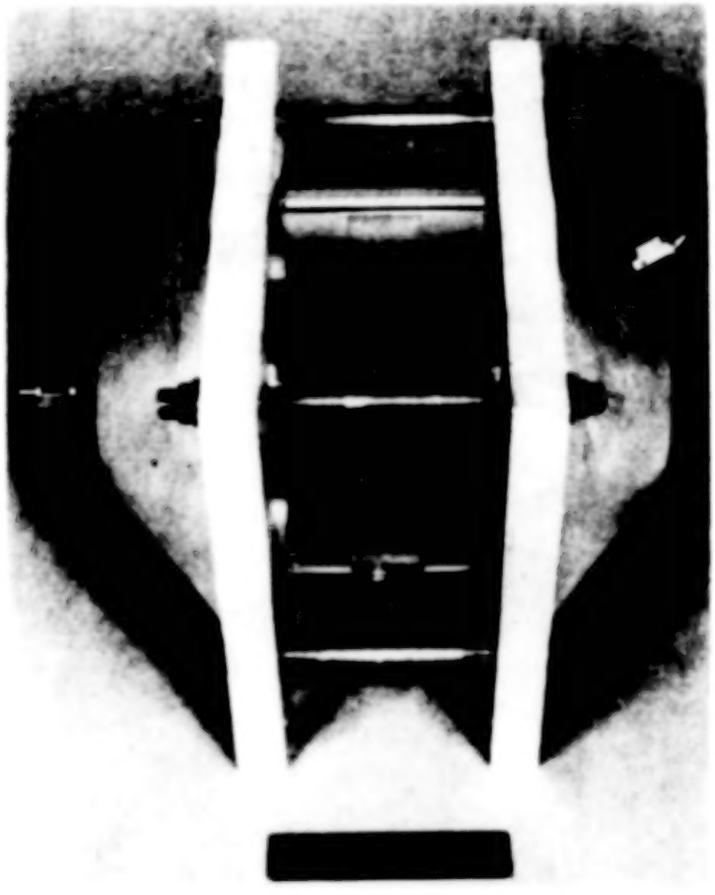

Figure 9

The experiment will be activated in orbit by astronaut command using the shuttle Autonomous Payload Control System (APCS). The APCS operates three GAS Control Decoder (GCD) relays in the base of the GAS canister.

GCD Relay A will be switched from latent to hot to activate the experiment and measure background radiation levels with a dry test tank using the nucleonic gaging system.

GCD Relay B will then be operated to (1) turn on the movie camera and lights, (2) inject 800 ml of Freon into the test tank, and (3) record gaging system and temperature data for three minutes.

Finally, GCD Relay C will be operated for another 3 minutes to record data after injecting an additional 450 ml of Freon into the test tank.

OPERATING SEQUENCE: G522 EXPERIMENT

11-6207

GCD RELAY A	**TURNS DATA RECORDING SYSTEM ON FOR 3 MIN. TO MEASURE BACKGROUND RADIATION LEVELS**
GCD RELAY B	• **TURNS ON LIGHTS & CAMERA** • **ACTUATES VALVE TO INJECT 800 ML OF FREON INTO TEST TANK** • **RECORDS DATA FOR 3 MIN.**
GCD RELAY C	• **TURNS ON LIGHTS & CAMERA** • **ACTUATES VALVE TO INJECT 450 ML OF FREON INTO TEST TANK** • **RECORDS DATA FOR 3 MIN.**

Figure 10

The experiment passed flight certification testing (thermal and vibration environments) during the week of 21 April 1986 and is now ready for flight. As shown by the figure below, the flight certification sequence was similar to that employed for the G074 propellant acquisition experiment (Figure 5).

FLIGHT CERTIFICATION TESTS: G522 EXPERIMENT

11-6308

- PROOF PRESSURE
- ROOM TEMPERATURE MISSION SEQUENCE
- HIGH TEMPERATURE MISSION SEQUENCE
- LOW TEMPERATURE MISSION SEQUENCE
- VIBRATION TEST
- ROOM TEMPERATURE MISSION SEQUENCE

Figure 11

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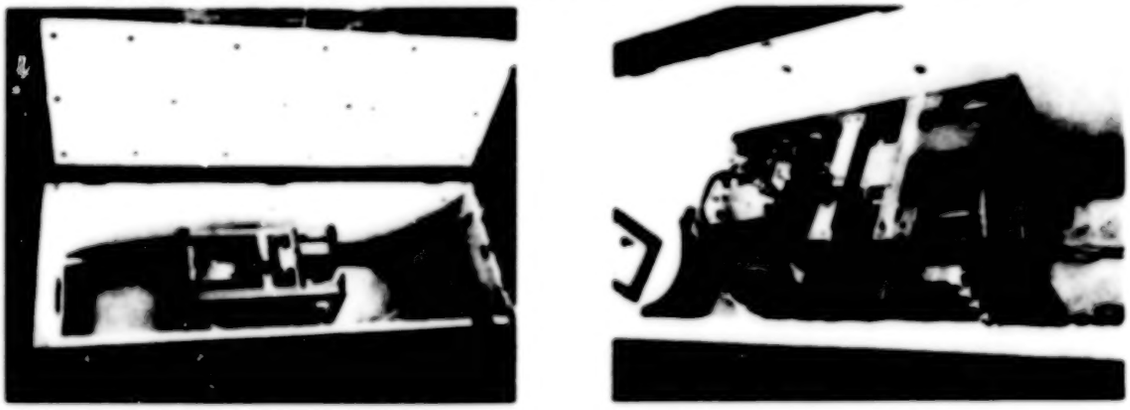
For thermal testing the experiment was placed in an insulated enclosure (Figure 12). First, liquid nitrogen was circulated through a finned heat exchanger in the base of the enclosure to achieve a stable experiment temperature of approximately -20°C. A fan inside the enclosure circulated the air to obtain a uniform temperature distribution. When the temperature stabilized, the experiment was operated for a complete mission sequence, and all functions were normal.

For the high temperature test, steam was circulated through the heat exchanger to obtain an experiment temperature of 45°C. Another mission sequence was run following temperature stabilization, and, again, all experiment functions were normal.

THERMAL TESTS OF G-522 EXPERIMENT

11-6235

EXPERIMENT INSTALLED IN THERMAL CONDITIONING ENCLOSURE



CONTROL & DATA MONITORING SYSTEM FOR THERMAL TESTS

Figure 12

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The setup for random vibration testing is shown in Figure 13. The experiment was subjected to the NASA-specified spectra of 6 g's RMS for 40 seconds in each of its three principal axes. Following vibration testing, a mission operating sequence was run, in which all experiment functions were normal.

As a result of these successful environmental tests, the experiment has been placed in storage to await a shuttle flight assignment. After storage, additional room temperature operational checks will be performed to verify the experiment is ready for flight.

VIBRATION TESTS OF G-522 EXPERIMENT

EXPERIMENT INSTALLED ON VIBRATION TABLE

INSTALLATION OF SHIPPING CYLINDER

SHUTTLE Z-AXIS VIBRATION TEST

Figure 13

A breakdown of failures experienced on GAS experiments to date is presented below. This survey was prepared by Dr. Ridenoure of Utah State University, and the results will be presented in detail at the 1986 Get-Away-Special Experimenter's Symposium to be held at NASA-Goddard this October. As shown, the failures can be categorized in five primary areas, with 6% of the failures having unknown causes.

Because of the high failure rate, all future GAS experiments should be subjected to shuttle thermal and vibration environments.

SURVEY OF GAS EXPERIMENTS FLOWN ON SHUTTLE (DR. RIDENOURE – UTAH STATE UNIVERSITY)

11-6309

- 54 SUCCESSES
- 80 FAILURES (EXPERIMENT OBJECTIVES NOT ACHIEVED)
- CAUSES OF FAILURES
  - 33% THERMAL (TEMPERATURES TOO LOW)
  - 25% CONTROLS (FAILURE TO ACTIVATE)
  - 14% MECHANICAL (FAILURE DUE TO VIBRATION)
  - 12% POWER (BATTERIES WENT DEAD)
  - 10% ATMOSPHERE (CANISTER LEAKED)
  - 6% UNKNOWN

Figure 14

Based on the results of Dr. Ridenoure's survey and experience gained in building two McDonnell Douglas experiments, a summary of recommendations for designing and testing future GAS payloads is presented in Figure 15.

SUMMARY
RECOMMENDATIONS FOR GAS PAYLOADS

11-6310

- PROVIDE SIMPLE, RUGGED DESIGN
- PROVIDE HIGH MARGIN FOR BATTERY POWER & LIFE (GATES LEAD-ACID & YARDNEY SILVER-ZINC & SILVER-CADMIUM CELLS ARE GOOD CHOICES)
- QUALIFY EXPERIMENT TO SHUTTLE ENVIRONMENTS
  - MINUS 20°C IF NO HEATERS ARE USED
  - NASA-GODDARD SPECIFIED VIBRATION ENVIRONMENT (6 G RMS)
  - CONDUCT COMPLETE OPERATIONAL TESTS
- AVOID ACTIVATION DURING BOOST. OTHERWISE, USE NASA-GODDARD REDUNDANT BAROMETRIC SWITCHES

Figure 15

References

1. Orton, G. F.: Design and Development of Shuttle Get-Away-Special Experiment G-074. NASA Conference Publication 2324, August 1984.

2. Orazietti, A.J.; Orton, G.F.; and Schreib, R.: Propellant Gaging for Geostationary Satellites. AIAA Paper 86-1716, June 1986.

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SHUTTLE MIDDECK FLUID TRANSFER EXPERIMENT - LESSONS LEARNED

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Martin Marietta Aerospace
Denver, Colorado

This presentation is based on the experience gained from having integrated and flown a shuttle middeck experiment. The experiment, which demonstrated filling, expulsion, and fluid behavior of a liquid storage system under low-gravity conditions, is briefly described. The advantages and disadvantages of middeck payloads compared to other shuttle payload provisions are discussed. A general approach to the integration process is described. The requirements for the shuttle interfaces--such as structures, pressurized systems, materials, instrumentation, and electrical power--are defined and the approach that was used to satisfy these requirements is presented. Currently the middeck experiment is being used as a test bed for the development of various space fluid system components.

A shuttle middeck experiment that was flown provided first-hand experience regarding the integration and operations process. Selection of the experiment concept and definition of the design parameters had to be carefully tailored to the integration and safety requirements. The experiment was very successful, with no hardware problems being experienced during the flight operations. All objectives were achieved, providing valuable data on fluid behavior under low-gravity conditions (Refs 1 and 2).

INTRODUCTION

Presentation is based on experience gained from Storable Fluid Management Demonstration (SFMD).

- o Shuttle middeck secondary payload
- o Experiment operated flawlessly on STS Mission 51-C, January 1985
- o Joint endeavor among Martin Marietta, NASA, and USAF
- o Objectives successfully achieved:
  1) Low-g refill of tank
  2) Low-g expulsion of tank
  3) Low-g fluid behavior

Figure 1

The ways in which the Shuttle Orbiter can carry payloads into orbit are listed below. Selection of the mode for a given payload is dependent upon a number of factors.

Concentrating on middeck payloads, their limits are defined below. The advantages and disadvantages of middeck payloads are listed. The suitability of a middeck payload in achieving the experiment objectives must be evaluated.

PAYLOAD CONSIDERATIONS

o TYPES OF PAYLOADS

MIDDECK:
- Carried in locker
- Installed in lieu of lockers

PAYLOAD BAY:
- Get Away Special
- Installed on truss, pallet, etc.
- Spacelab

o STANDARD MIDDECK PAYLOAD

Less than 3 locker volumes
Less than 130 pounds
Electrical power limits
Passive cooling

o MIDDECK PAYLOAD IN LIEU OF LOCKERS

ADVANTAGES	DISADVANTAGES
Direct astronaut involvement - Operation, monitoring, contingency	Limited weight and size Limits on flight opportunities - Priorities, size of crew, crew time
Simple structural interface	Constraints on test liquids
Cost effective	
Available data acquisition	

Figure 2

After the shuttle interface and safety requirements are understood, an approach to verifying that the payload satisfies these requirements should be defined. Safety reviews and design reviews will establish the suitability of the approach. Safety is the prime concern.

INTEGRATION APPROACH

- o Interface Control Document (Ref. 3) and Shuttle Safety Documents define requirements imposed on payload
- o Payload design and verification plan establishes how requirements are met
- o Safety reviews verify that approach adequately satisfies safety requirements
- o Payload functioning and reliability is responsibility of payload organization

Figure 3

The safe design of pressurized systems requires that worst-case operating conditions be defined and the proper design margins be selected. The approach used for the transparent plastic tanks and the plumbing system of the SFMD is presented here.

FLUID SYSTEM DESIGN

MOP - Maximum operating pressure (pressure at which the system actually operates)

MAWP - Maximum allowable working pressure (a worst-case condition)

o Pressure Vessels - no fracture control

Proof Pressure	- 1.6 x MAWP
Burst Pressure	- 4 x MAWP
Collapse Pressure	- 2 x MOP
Pressure Cycles	- 1.5 x MOP applied 2 times maximum number of cycles

Compensate test pressures for maximum temperature when performing room temperature test

o Lines and Fittings

Diameter less than 1.5 inch - ultimate safety factor of 4
Diameter greater than 1.5 inch - ultimate safety factor of 1.5

Figure 4

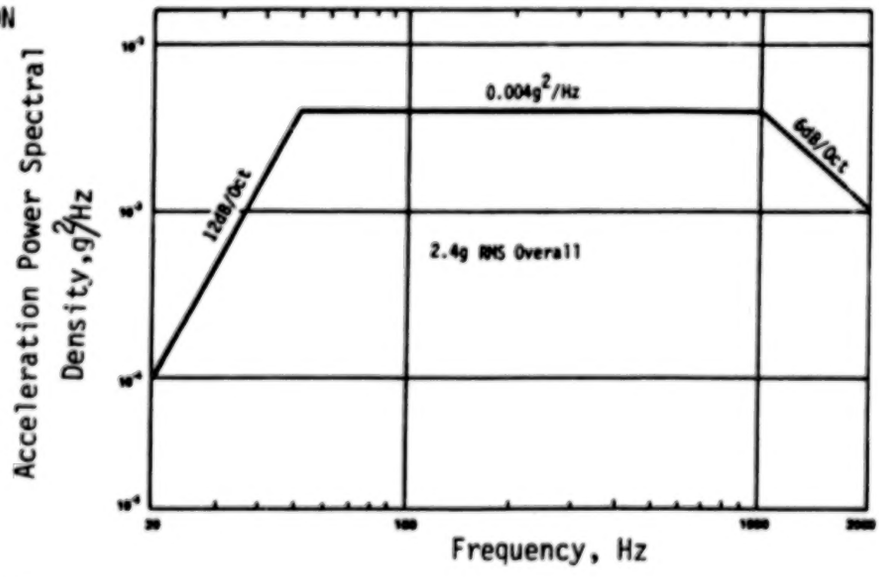
Steady and vibrational loads were combined to produce the load factors in the table below. The random vibration environment was specifically derived from measurements in the middeck area. These qualification levels are applied for one minute in all three axes. Structural design proceeds from these requirements and the factors of safety listed below.

STRUCTURAL DESIGN

o LOADS

Event	Load Factor (g)		
	X	Y	Z
Lift-off	+2.4/-5.6	± 2.0	± 5.5
Landing	± 7.5	± 4.0	+12.0/-10.0
Emergency Landing	+20.0/-3.3	± 3.3	+10.0/-4.4

o RANDOM VIBRATION



o FACTORS OF SAFETY

Yield - 1.6 times limit load
Ultimate - 2.25 times limit load

Figure 5

Selection of materials must consider their safety related properties: toxicity, off-gassing, flammability, hazardous debris (e.g., broken glass), etc. Materials certification is required unless off-gassing tests are performed. The same requirements apply to test fluids.

MATERIALS

- o Metals and Non-Metals

  Select approved materials from references such as: JSC 02681, Non-metallic Materials Design Guidelines and Test Data Handbook or, perform off-gassing test of selected materials

- o Test Liquids

  Water is preferred (for example, allowable concentration of Freon 113 in cabin air is 50 ppm)

- o Pressurant Gas

  Air is preferred

Figure 6

For middeck experiments, Orbiter standard equipment can be used for the acquisition of data. Still cameras, movie cameras, and video recording equipment are available. Video recording is effective since a sound track and time can be combined with the scene and data quality can be verified while it is being recorded. Photo lights are also available.

The SFMD used mechanical gauges to record pressure and temperature. A built-in lighting system and flowmeter with digital readout are being incorporated.

INSTRUMENTATION AND DATA

- o Standard Orbiter Equipment

  Video cameras - combine voice annotation and time with video

  Lighting - standard equipment available

- o SFMD Instrumentation

  Pressure gauges
  Thermometer
  Sight flow indicator
  Flowmeter

Figure 7

Up to 5 amps of DC power is available in the middeck for payload use. Payload must provide connector to interface with Orbiter provided cable. Interface requirements include proper electrical design and fusing, and the electromagnetic compatibility requirements listed below.

The SFMD used no Orbiter power on its first flight. The lighting system now being incorporated introduced many complications, e.g., EMI filtering, heat dissipation, and flight qualified electrical component procurement.

ELECTRICAL POWER

- o DC power available for payloads
  - Maximum of 5 amps
  - On-orbit use only
- o Electromagnetic Compatibility
  - Susceptibility
  - Conducted emissions
  - Radiated emissions
  - Magnetic field
  - Switching transient
- o Electrical Bonding

Figure 8

Having flown once, the SFMD is a fully integrated and proven middeck payload. Plans for the continued use of the SFMD, through refurbishment and reverification as required, have been implemented. Within certain limitations, the SFMD can accommodate various tank shapes and components for development testing of fluid storage systems. A document defining how the SFMD may be used for such testing is available.

USE OF SFMD AS TEST BED

- o Fully integrated and flight proven test bed for space fluid storage system development
- o New experiments can be installed with well defined interfaces
  - Interface at wall of previously qualified tank
  - Interface of new tank with mounting flange
- o SFMD Interface Control Document available

Figure 9

In summary, this presentation has discussed how a middeck payload is an effective means of performing experiments in space. An approach of developing an understanding of interface requirements while preparing a verification plan for the payload was found to be successful. It is important to begin coordinating safety concerns, Orbiter equipment requirements, and crew involvement as early as possible.

SUMMARY

- o Orbiter middeck payloads are an effective way of performing experiments on the Space Shuttle
- o Obtain a thorough understanding of interface requirements and define experiment verification approach
- o Begin coordinating integration early in program

Figure 10

References

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3. "Orbiter Middeck/Payload Standard Interfaces Control Document," ICD-2-1M001, NASA Johnson Space Center, March 1984.

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15. Supplementary Notes

16. Abstract

The NASA Microgravity Fluid Management Symposium, held at the NASA Lewis Research Center, September 9 - 10, 1986, focused on future research in the microgravity fluid management field. The symposium allowed researchers and managers to review space applications that require fluid management technology, to present the current status of technology development, and to identify the technology developments required for future missions. The 19 papers covered three major categories: (1) fluid storage, acquisition, and transfer, including discussion of topics such as fluid sloshing, modeling of cryogen in low gravity, and fluid mixing and temperature destratification; (2) fluid management applications, including discussion of topics such as space power and thermal management systems and environmental control and life support systems; (3) project activities and insights that included two descriptions of previous flight experiments and a summary of typical activities required during development of a shuttle flight experiment. A discussion followed each presentation, and a general discussion at the end of the symposium led to four general recommendations.

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